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An Evaluation and Analysis of Past Landfill Closures in Puerto Rico as Guidance for Current and Future Closures

STREAMS Task Order 99

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Executive Summary

The Resource Conservation and Recovery Act of 1976 (RCRA) establishes the minimum standards for the design, operation, and closure for municipal solid waste landfills in the United States and its territories. In Puerto Rico, the Regulations for Non-Hazardous Solid Waste Management provide the framework for compliance with RCRA. In the past, landfills in Puerto Rico have not always been closed in accordance with the minimum federal and state regulations. Various issues including the use of appropriate materials for closure, installation and utilization of environmental monitoring equipment, and waste mass stability have raised questions regarding the impact of these facilities on human health and the environment.

The United States Environmental Protection Agency's (US EPA) Office of Research and Development (ORD), in cooperation with US EPA Region 2, contracted RTI International (RTI) to evaluate past landfill closures in Puerto Rico and provide recommendations for current and future closures. Innovative Waste Consulting Services, LLC (a subcontractor to RTI), and representatives of US EPA ORD traveled to Puerto Rico in March 2011 to conduct several site investigations at closed landfills in different geographic regions of the island. Four landfills were visited and the conformity of the site to closure criteria in federal and Commonwealth regulations was evaluated. The field team conducted visual assessments, measured surface methane emissions, and measured the hydraulic conductivity of the final cover soil at the sites.

The following are recommendations to address issues at the landfills targeted in this study based on the field evaluations and subsequent historical document review:

Conduct a detailed final cover analysis to more accurately assess the extent of final cover construction as well as hydraulic performance of the in-place soils.

Evaluate groundwater quality and the presence of subsurface gases.

Identify potential beneficial uses for the sites.

In addition to the above specific recommendations to address the closed landfills visited during this project, the following recommendations are offered that may help improve landfill closures in the future.

Install and maintain access control infrastructure at all MSW landfills.

Install and maintain the minimum-required final cover or consider alternative, performance-based cover systems, such as evapotranspiration covers.

Design and construct above-grade side slopes to a maximum 3:1 (H:V).

Design and install stormwater management infrastructure.

Maintain existing gas collection infrastructure.

Monitor groundwater and perimeter gas.

Construct and maintain leachate collection systems and conduct a comprehensive assessment of leachate quality and leachate management on the island.

Assess beneficial use options for other closed landfills or landfills that will be closed in the near future.

Based on the results of the field visits, additional evaluation of other closed landfills in Puerto Rico is warranted, which would include a more detailed assessment of potential risk to human health and the environment, and perhaps an assessment of options to mitigate these potential risks. A combination of field testing, anecdotal information collection from municipality officials and local regulatory agencies, and historical document review could provide US EPA with the necessary tools to assist decision makers on how to best move forward with addressing closed landfills of concern.

Introduction

Project Background

The island of Puerto Rico has faced several challenges related to the issue of closed landfills – historically, many municipal landfills in Puerto Rico were not closed properly or abandoned, while others were closed in accordance with applicable rules but have sustained physical changes from climatic and human events that have rendered them less secure. As a result, some closed landfills may pose a risk to human health and the environment presently and in the future. The Office of Research and Development, United States Environmental Protection Agency (US EPA) awarded Task Order 99, "An Evaluation and Analysis of Past Landfill Closures in Puerto Rico as Guidance for Current and Future Closures" under its Scientific, Technical, Research, Engineering, and Modeling Support (STREAMS) contract to RTI International (RTI). RTI subcontracted a portion of the technical work to Innovative Waste Consulting Services, LLC (IWCS). The project was conducted to provide US EPA Region 2, whose jurisdiction includes Puerto Rico, with information to understand the current conditions of a subset of closed landfills and provide Region 2 personnel with recommendations for evaluating future closed landfills in Puerto Rico.

A field study was developed to evaluate four municipal solid waste landfills (representing different geographic regions in Puerto Rico) over the course of two field days (with approximately 3 to 4 hours spent at each site) by gathering information through observation and conducting limited field testing to understand the successes and shortcomings of previous closures. The field data were then supplemented by reviewing available historical documentation for each of the four subject sites to understand what, if any, engineering design or controls were put in place at the time the landfill closed.

Report Organization

This report is organized into five sections. Section 1 provides an introduction to the project. Section 2 describes the analysis methodology. Section 3 presents a discussion of the site selection, historical information review, and field study results. Section 4 provides a discussion of the project results and recommendations for future study. Section 5 lists the references used in developing this report.

Supplemental information is provided in a series of appendices. Appendix A contains USGS Quadrangle maps for each site. Appendix B includes a log of photographs taken during each site visit to supplement those included in this report. Appendix C, D, and E include calculation packages to estimate hydraulic conductivity at three of the sites. Appendix F provides supplemental figures for the sites visited.

Analysis Methodology

The first task of the project was to develop a set of criteria that would be used to evaluate each of the selected sites. Given the screening-level nature of the project, the project team worked to develop evaluation criteria that could be used to efficiently assess conditions (since the project scope included an aggressive schedule of visiting four sites spread across the island in two days) at a given site while causing minimal disturbance to the site. The project team held several telephone conferences in late 2010 and early 2011 to develop the site evaluation criteria. Ultimately, the field schedule and the desire to collect data during field visits guided the decision-making process. A quality assurance project plan (QAPP) was developed and submitted to the US EPA QA officer for approval prior to beginning the field visits.The following sections describe the major elements of the plan that were developed to evaluate the closed sites.

Field Observations

The intent of the field observations was to evaluate the presence and condition of monitoring and control structures at the site as well as observe the overall condition of each site. The assessment was intended to be only qualitative in nature. The specific items or conditions that were targeted during the field observation of each site included:

Access control (e.g., fencing, locking gate, signage)

Cover soils (presence or absence, evidence of erosion, presence or absence of vegetation)

Stormwater controls (evidence of ponding, presence or absence of stormwater control infrastructure and condition of such infrastructure)

Leachate controls (presence or absence)

Nuisance conditions (presence or absence of windblown litter, leachate seeps, odors, and disease vectors)

Environmental monitoring and/or control infrastructure (presence or absence of gas monitoring wells, groundwater monitoring wells, and gas collection wells)

Each metric was evaluated through sensory observation and documented with photographs.

Hydraulic Conductivity of Site Cover Soils

The Resource Conservation and Recovery Act (RCRA) established the minimum design standards for municipal solid waste (MSW) landfills in the United States and its territories, which includes design criteria for final cover soils at landfills.

According to 40 CFR 258.60(a)(1), all MSW landfills must have, at a minimum, a final cover system constructed to “have a permeability less than or equal to the permeability of any bottom liner system or natural subsoils present, or a permeability no greater than 1×10^{-5} cm/sec, whichever is less.” Rule 565 of the Puerto Rico Regulations for Non-Hazardous Solid Waste Management established the same minimum criteria. Given that the subject facilities for this project are old, closed landfills, the hydraulic conductivity criterion of 1×10^{-5} cm/sec was used as an evaluation metric.

Hydraulic conductivity can be measured in the field and in the laboratory through different empirical and experimental methodologies. The apparatus selected to measure field hydraulic conductivity of soils for this project was the Guelph Permeameter (Soilmoisture Equipment, Santa Barbara, CA). The instrument is a constant-head device that operates on the Mariotte siphon principle. This device was selected because a given test can be completed in a couple of hours and the unit is fairly easily transportable. Figure 2-1 shows the permeameter in use at one of the sites visited during the study.

Figure 0-1. Guelph Permeameter in use at the closed Rincón Landfill

Figure 2-2 presents a flow chart that shows the decision-making process that was used in the field as part of taking a hydraulic conductivity measurement.

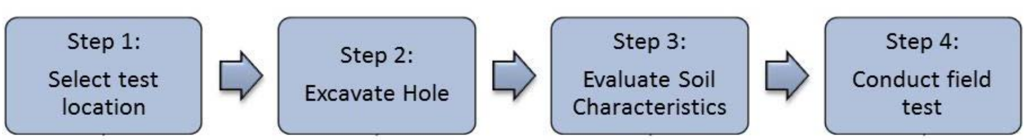

Figure 0-2. Guelph Permeameter Field Test Flow Chart

Step 1: The field team identified areas of the landfill that were fairly flat and free of debris and thick vegetation and the specific area for the test was selected.

Step 2: At the selected sampling location, a borehole was advanced using a hand-held auger until the desired depth was reached (typically 4 to 6 in. below grade). If a borehole could not be advanced this deep (from refusal because of a rigid object or if the borehole could not maintain its integrity), Step 1 was repeated. A stiff-bristle brush was used to prepare the borehole so that the smearing effect (which could provide erroneous measurements) would be reduced.

Step 3: During borehole advancement, the auger's spoils were visually classified using a soil classification guide provided in the permeameter user manual. Step 4: The equipment was assembled, the appropriate testing method was selected, and the hydraulic conductivity measurement process was initiated. Figure 2-3 shows a simplified schematic of the Guelph Permeameter.

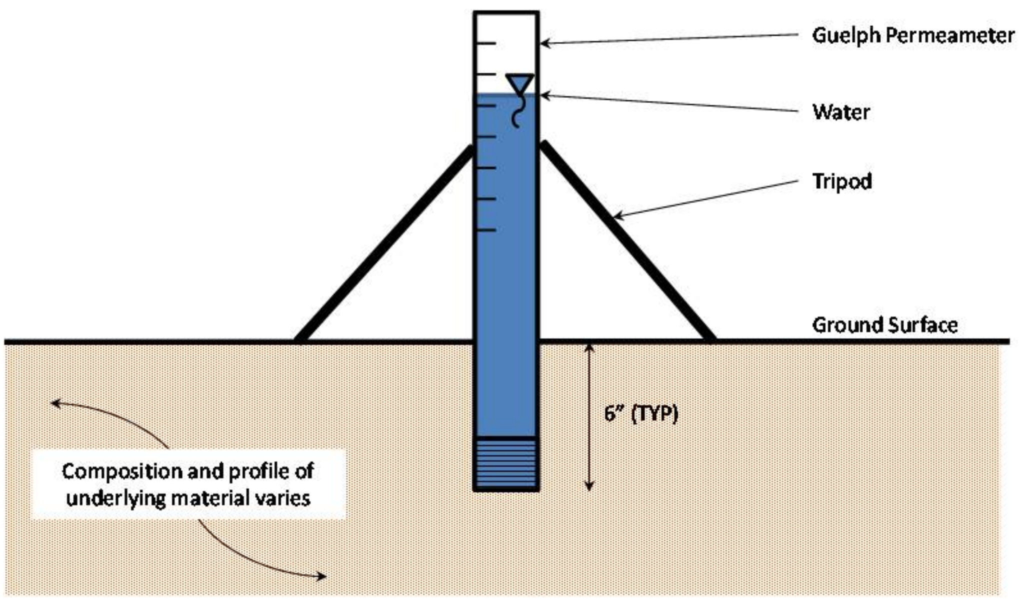

Figure 0-3. Conceptual Schematic of Guelph Permeameter Apparatus

Prior to initiating measurements, the permeameter was assembled and centered over the borehole, and the outlet tip was lowered to the bottom of the hole. The reservoir was filled with water (about 2 gallons) and was then sealed with the supplied cap. The instrument includes two reservoirs: an inner reservoir (used alone if the percolation rate is expected to be low) and an outer reservoir (used in combination with the inner reservoir when percolation rates are expected to be relatively high).

A one-head or a two-head procedure can be used with the instrument. The one-head procedure allows for more rapid measurement of hydraulic conductivity. The one-head procedure was selected for measurement at all sites because of the expected percolation rate and the number of sites that were targeted for analysis, which was also consistent with the time available to conduct the field study.

Once the reservoir configuration was selected, the test was started by raising the upper air tube and water height indicator to a constant head of 5 cm. As the water percolated into the soil, the water level in the reservoir(s) fell. Readings were taken using the internal graduated cylinder over a given time interval, typically ranging from a 1-minute interval (in cases where water moved fairly quickly into the soil) to a 3-minute interval (when water percolated more slowly through the soil).

The rate of fall was calculated throughout the procedure by dividing the drop in water level by the time interval between readings. Once the rate of fall stabilized for a minimum of three consecutive readings, the steady-state rate of fall was calculated and the measurement procedure was concluded.

After obtaining the steady-state rate of fall from the permeameter, the data collected in the field were used to calculate the hydraulic conductivity using procedures and equations provided in the instrument's manual. The hydraulic conductivity of the selected cover soil at each site was then compared to the RCRA and the Puerto Rico Non-Hazardous Solid Waste Management criterion of 1×10^{-5} cm/sec.

Methane Surface Emissions Monitoring

Methane surface emissions monitoring is typically performed at MSW landfills to help evaluate the operations of an active gas collection system and is not typically required as part of post-closure care activities at facilities that do not have active gas collection. The New Source Performance Standards (NSPS) for MSW Landfills (Subpart WWW) sets methane concentration limits (500 parts per million (ppm)) above which additional action must be taken to remediate issues with the gas collection system. Although none of the sites targeted for this project were expected to have active gas collection, the project team used the 500 ppm level as an initial criterion with which to compare measurements of methane surface concentrations at each targeted site.

A portable TVA Foxboro 1000B Vapor Analyzer with a flame ionization detector (FID) was used to measure methane surface concentrations at each of the targeted landfills. The instrument was operated using the "scan" mode whereby samples for methane concentration (in units of ppmv) are collected continuously by the instrument. The instrument was powered on, the internal flame was ignited, and the instrument ran for approximately 10 minutes (per the instrument's operating manual) prior to starting calibration procedures. The instrument was calibrated using a certified 500-ppm methane standard in accordance with the instrument's operating procedures.

Where access was available, an upwind and a downwind background reading (based on the assumed limits of the landfill and wind conditions at the time of measurement) were taken with the instrument. The operator then slowly traversed the landfill unit's surface in a serpentine pattern at a spacing of approximately 100 ft, taking methane concentration measurements continuously with the instrument's sample probe located 2 to 4 inches from the landfill's surface. The path traveled on each landfill surface was determined based on the conditions in the field and generally avoided large obstructions (e.g., vegetation or debris) and steep slopes (greater than a 3 horizontal to 1 vertical). Figure 2-4 shows a project team member taking a reading with the portable FID.

Figure 0-4. Field Team Member Taking a Reading with the Portable FID

A hand-held readout device was monitored by the operator during measurement. If the detected methane concentration began to increase, the operator paused and waved the monitoring probe above the surface to find the potential area of high methane concentration until the reading stabilized. Initially, the project team intended to note all locations where a reading greater than 500 ppm was measured; however, as a result of the low concentrations measured in the field, all measured concentrations above the background levels were noted and recorded in a field log book.

Historical Information Review

The project team completed the site selection process a couple of weeks prior to mobilizing – as described in Section 3.1, the targeted sites and the sites that were accessible differed slightly. Given the fluid nature of the selected sites, historical documentation for each of the sites that were visited was requested from the local Puerto Rico regulatory agency, Junta de Calidad Ambiental (JCA) immediately following completion of the field visits. The documents that were available to the project team included historical design documents for two of the landfills that were visited (Rincón 1 and Cabo Rojo). Limited additional information was found on the other two sites that were visited through literature searches, information provided by the US Fish and Wildlife Service, and publicly-available sources.

The historical information was used to attempt to fill data gaps that existed based on observations made during site visits. Available historical information was reviewed to understand basic site characteristics such as the operating years, type of waste received, and area and depth of waste disposal. Additionally, the historical information was reviewed to identify potential regulatory compliance issues, evaluate whether a formal closure plan was designed for each facility and what the details of those closure plans were as well as whether the closure plan was followed (in whole or in part) based on field observations.

Field Evaluation

Sites Evaluated

The project team initially targeted four closed landfill sites to evaluate during the field effort: Rincón, Cabo Rojo, Guayanilla, and Vieques. These sites were targeted since they represent different geographical regions of the island with somewhat varying climatic conditions. Before the field visits, it was unknown whether these facilities were formally closed with appropriate engineering controls in accordance with US EPA and JCA rules or were abandoned or perhaps partially closed. Ultimately, the actual sites visited changed slightly from the initial target list - Table 0-1 summarizes the sites of interest and provides notation on those that were visited and those that were targeted but not visited. Figure 3-1 shows the approximate location of each of the six landfills presented in Table 3-1.

Table 0-1. Closed Landfill Sites of Interest Targeted During the Project

Site	Visited During Field Effort?	Notes
Cabo Rojo	Yes	Visited on 28 March.
Guayanilla	No	Attempted to visit on 28 March – municipality officials corresponded with JCA and said the gates to the facility were locked and thus access was not possible.
Rincón (1)	Yes	The project team was not aware of this site before arriving in Puerto Rico. The JCA representative that accompanied the project team on 28 March brought the project team to this facility.
Rincón (2)	Yes	This was the originally-targeted closed landfill in the municipality, which is located along the west coast of Puerto Rico. Visited on 28 March.
Vega Alta	No	The project team attempted to secure an escort to accompany the team to the site on 30 March. The short notice of the request prevented a municipality official or a JCA official from accompanying the project team. Limited locational data for the site were available and attempts to find the site were not successful.
Vieques	Yes	Visited on 29 March.

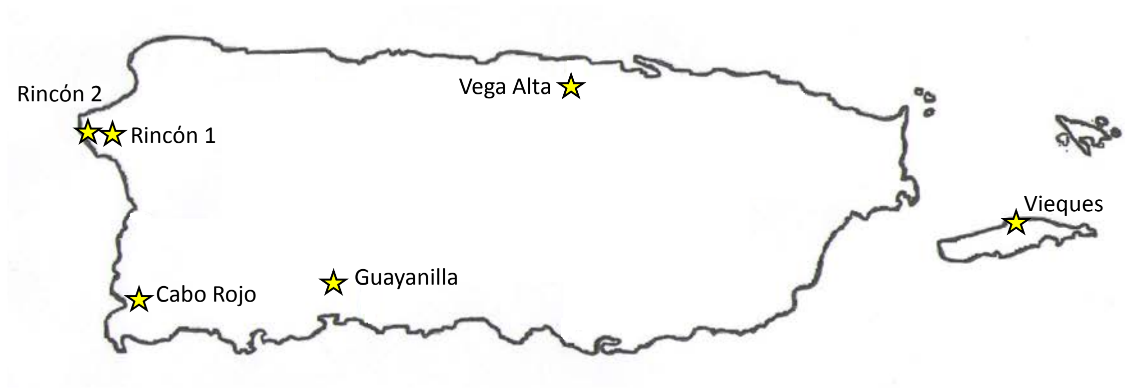

Figure 0-1. Location of Selected Closed Landfill Sites of Interest in Puerto Rico

Rincón Landfill 1

Background Information

The Rincón Landfill (denoted in this report as Rincón Landfill 1) is located about 0.6 km southeast of the center of the Municipality of Rincón off of PR-115 (at approximately 18°20'3.57"N, 67°14'42.90"W). The landfill reportedly began operation in 1982 (Garcia, Cabot, & Asociados 1994). On 10 August 1993 the JCA issued an order to the Municipality of Rincón to close the landfill (JCA 1996a). A closure plan for the site, prepared in March 1994 by Garcia, Cabot, & Asociados, describes the site as lying on the north-facing slope of a northeast-striking mountainous ridge terminating at a stream to the north, Quebrada los Ramos. Furthermore, the closure plan reported a landfill property area ranging from 8.5 acres to 10 acres and a disposal footprint of approximately 6 acres, consisting of municipal solid waste, scrap iron, and tires (Garcia, Cabot, & Asociados 1994). The landfill was apparently phased by filling in the southwestern areas of the site and the adjacent valley. A 1966 USGS quadrangle map (which would represent pre-development grades based on information provided in the closure plan) shows the site topography sloping gently generally towards the stream with two high points of elevation just to the south and east-southeast of the landfill – a copy of the USGS quadrangle map for this and the other sites visited is provided in Appendix A.

Figure 3-2 shows an aerial photograph of the site and an inferred waste boundary based on information provided in the site's closure plan. A seismic refraction investigation prepared as part of the closure plan development suggested that the waste in the center of the site was approximately 4 to 5 m thick. Additionally, the closure plan reported that approximately 103,700 tons of waste were disposed based on the years of operation (1982 – 1994) and census figures and information from the Puerto Rico Planning Board and Waste Management Authority. The site was to cease accepting new waste in April 1994 and the closure was to be certified in October 1994.

The closure plan described several components of the closure system in general terms, but drawings, details, and specifications were not available. The site's final cover was intended to have an 18-in. thick clay layer overlain by a high-density polyethylene geomembrane liner of unspecified thickness, and a 6-in. to 8-in. thick vegetative soil layer. The closure plan also mentions that access, vector, fire, and leachate would all be controlled. Additionally, the plan indicates that a gas collection system would also be put in place as well as a gas and groundwater monitoring system. The plan proposed three groundwater monitoring wells (identified as 1, 2, and 3) that would be used to monitor groundwater quality upgradient and downgradient of the landfill.

Several pieces of correspondence were made available to the project team regarding the site. A Closure Inspection Report prepared by JCA dated July 1996 noted several items in the Closure Plan that had been addressed or were being addressed at the time of the inspection (JCA 1996a). Among those notes was that a clay layer was being installed at the time of the inspection and that nine gas monitoring wells had been installed. During the inspection, one groundwater monitoring well was vertically extended so that once the installation of the final cover was complete, the well would remain accessible. The municipality had also begun leveling the south slope of the landfill.

The inspection report pointed out that several elements required under the August 1993 Closure Order had not been fulfilled at the time of inspection. In the inspection report, JCA requested the remediation of several shortcomings in the closure of the site including:

Application of a final 6-in soil erosion layer capable of supporting vegetation.

Implementation of a system to control leachate.

Submission of groundwater monitoring and explosive gas monitoring plans in accordance with the prescribed regulations

Determination of the exact locations of each groundwater monitoring well installed on the south slope.

A follow-up inspection in October 1996 found the same deficiencies at the site.

The Municipality of Rincón later submitted a request to JCA to develop an ornamental plant nursery as an alternative use of the landfill during the post-closure period (a copy of this request was not available to the project team, but its existence was revealed in a March 2002 JCA response to the request). In its March 2002 response to the request, JCA indicated that multiple requests (30 May 1996, 30 July 1996, 10 December 1996, and 20 March 1997) had been made by JCA to the municipality to complete closure activities in accordance with the closure plan submitted to and approved by the governing board. JCA noted that the site had not yet complied with all of its requirements for closure, and that in order to implement an alternative use of the landfill a series of conditions must be met including:

The municipality must submit a notification to JCA signed by an engineer licensed in Puerto Rico that certifies closure activities were performed in accordance with the closure plan submitted to and approved by the Board.

The municipality must make a note with the land registry indicating that the property was used as a landfill.

Signs must be maintained which identify the site as a closed landfill.

The final cover must be maintained to prevent erosion problems and exposure of buried waste.

The monitoring wells must be easily identified and accessed (three monitoring wells were identified as installed: MW-1, MW-2, and MW-3).

The monitoring wells must be flagged and labeled.

All monitoring wells must have a lock and a cap installed.

Integrity and structural tests on each well must be performed through use of a camera to check for blockages or breaks in the pipe.

Stormwater runoff channels must be built and maintained.

A leachate collection system must be built and maintained.

A groundwater monitoring plan must be prepared in accordance with RCRA guidance and submitted.

An explosive gas monitoring plan must be prepared and submitted.

Groundwater sampling must be initiated after JCA's approval of the groundwater monitoring plan.

Explosive gas monitoring must be initiated following approval of the plan by JCA.

In the March 2002 letter, the JCA also described the findings from a February 2002 site inspection. During the inspection, the JCA located three groundwater monitoring wells on site (MW-1, MW-2, and MW-3), evaluated the condition of the wells, measured the depth of each well, measured the depth to water in each well, and determined the material and diameter of the pipes. MW-1 and MW-2 were found to be dry. Table 0-2 provides the well data collected by JCA during the site inspection. Figure 3-2 shows the approximate proposed location of the wells according to the closure plan for the site—no as-built locational data was available for the wells.

Table 0-2. Groundwater Well Inspection Data from a 2002 JCA Site Inspection

ID	Gradient	Condition of the Steel Cover	Well Depth (ft)	Water Level (ft)	Product Level	Height and Diameter of Case	Well Diameter
MW-1	*Up gradient; Southeast*	*Acceptable; No Lock*	*93.18*	*Dry*	*None*	*58' 4"*	*2.0"*

Table 3-2 (continued)

ID	Gradient	Condition of the Steel Cover	Well Depth (ft)	Water Level (ft)	Product Level	Height and Diameter of Case	Well Diameter
MW-2	*Down gradient; North*	*Acceptable; No Lock*	*12.73*	*Dry*	*None*	*3.5’ 3.5”*	*2.0”*
MW-3	*Down gradient, West*	*Acceptable; No Lock*	*28.87*	*27.68*	*None*	*2.54’ 5.5”*	*4.0”*

JCA recommended that the municipality run integrity tests on the wells to evaluate the presence of obstructions or breaks in the wells. They further recommended that the wells be evaluated for future use in monitoring activities at the site. The March 2002 letter is the last piece of correspondence that was available to the project team.

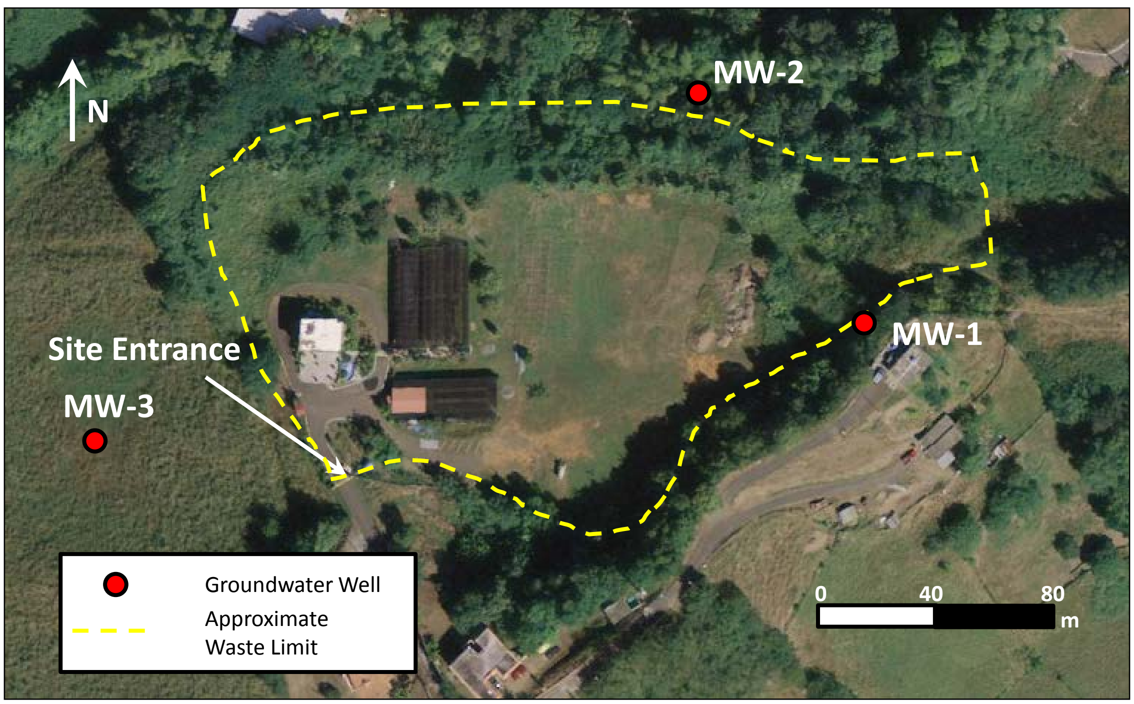

Figure 0-2. Aerial Photograph of Rincón 1, Inferred Waste Boundary, and Approximate Location of Groundwater Monitoring Wells

Field Observation Results

The site was visited on 28 March 2011. The conditions the day of the visit were partly cloudy with a temperature of 75 °F (Wunderground 2011a). The project team traveled to the site with guidance from Mr. Harold Gonzalez of JCA. The originally-targeted landfill identified in the planning stages of the project was thought to be located in the Municipality of Rincón along the coast – upon arrival at this site, the project team noted that the landfill was not located on the coast. The project team contacted the US EPA Region 2 regional representative, Mr. Carl Plössl, upon this discovery and after discussion with US EPA and the team, a decision was made to conduct only field observations and limited measurements at this newly-identified landfill so that the project schedule could still be maintained.

Although the entire perimeter was not accessible or visible at the time of the visit, fencing was in place along the southern edge of the property near the site entrance. The main entrance to the site, located to southwest of the site, had a gate and signage. A majority of the site (approximately two-thirds) was covered with a layer of mulch of indeterminate thickness (Figure 3-3). It was unclear whether a topsoil or clay layer was present beneath the mulch cover. Additional photos of the site are included in the photographic log in Appendix B.

Figure 0-3. Landscape View of Rincón 1 Looking to the North.

A plant nursery was present on the central-western portion of the site as well as three other buildings. The aerial photograph shown in Figure 3-2 was dated 2006 and appears to show the site as mostly vegetated, suggesting that the mulch layer has been placed in the last 5 years. The mulch appeared to consist mostly of ground-up dimensional lumber.

The site had a mostly flat terrain and the southern edge met with a near-vertical rock slope. The northern portion of the site's top deck declined at a steep slope (likely greater than 3 horizontal to 1 vertical). The steep slopes prevented detailed visual inspection of the slopes and the northern toe of the slope.

No leachate seeps were observed on the top surface of the landfill. Localized piles of newly-placed garbage (mostly bagged municipal solid waste and loosely-placed vegetative waste) were present at the northern edge of the site and a large pile of sorted plastics were found at the southern edge of the site (Figure 3-4). Information provided by an individual that was in one of the on-site buildings indicated that the Municipality of Rincón routinely picks up the bottles and hauls the bottles off site. Additionally, electronic waste was found in a small utility trailer near the entrance of the facility.

Figure 0-4. Stockpile of Sorted Plastics at the Rincón (1) Municipal Landfill

No objectionable odors or vectors were noted. While on site, a municipal employee visited with the project team and indicated that MSW is picked out of the waste deposits twice a week and that only yard waste is left on site. According to the employee, plastics are stockpiled and collected twice weekly.

No groundwater monitoring, subsurface gas monitoring, leachate control, or stormwater control features were observed on the accessible portions of the site. As described earlier, three monitoring wells were reportedly installed at the site as of 2002. The project team did not have possession of these historical data prior to the field visit and the field visit was limited to the apparent disposal portion of the footprint. Although exact locational data are not available for the three monitoring wells, the proposed locations in the site's closure plan indicate the wells may be located outside of the landfill's property boundary. The historical correspondence between the municipality and the JCA suggested that the groundwater monitoring wells were not readily identifiable (the correspondence requested that flagging and other high-visibility identifiers be installed at each well to facilitate discovery of the wells).

Field Measurement Results

Figure 3-5 shows the approximate waste limit based on historical information and the approximate methane surface emissions monitoring (SEM) path followed at the site. No methane surface concentrations exceeded 500 ppm during the monitoring period.

Furthermore, no concentrations of methane above background were detected. As mentioned previously, the field measurement was limited to only methane surface emissions so that the other targeted facilities could be visited within the project team's field schedule. The SEM path that was taken as shown in Figure 3-5 covers the portion of the site that had a mulch layer in place. The project team did not have historical information about the site's actual disposal footprint prior to the field study, so the SEM evaluation was limited to the area which the team suspected had historical waste disposal.

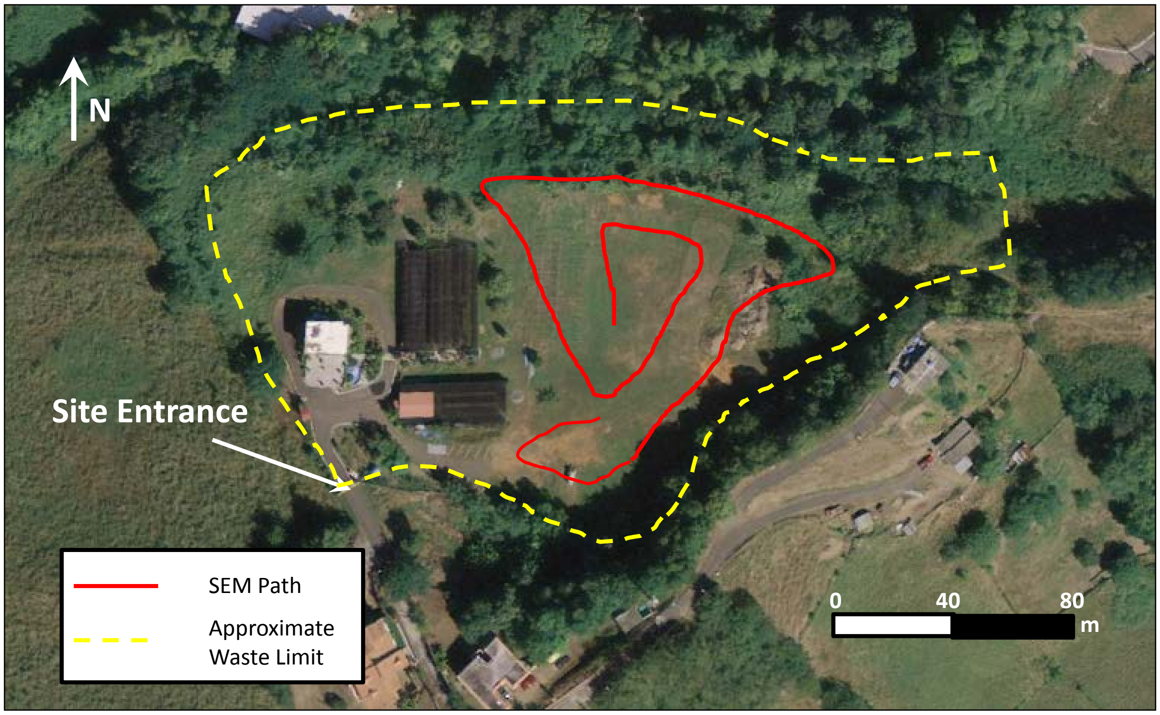

Figure 0-5. Surface Emissions Monitoring Path at Rincón 1

Rincón Landfill 2

Background Information

The second Rincón (referred to herein as Rincón 2) landfill occupies a stretch of the coastline of approximately 4.5 acres in western Rincón and is located off of PR-115 (at approximately 18°20'15.57"N, 67°15'13.98"W). Figure 3-6 shows an aerial photograph of the site and the approximate waste boundary based on an assessment of the field conditions, anecdotal information provided by local citizens that live on or near the site, and information provided by US EPA. The landfill was reportedly operated from the 1950s to the 1960s based on information contained in an e-mail written in 2009 from the US Fish and Wildlife Services to the US EPA Region 2 (US FWS 2009). Anecdotal information collected at the site suggested that the landfill was operated by the Municipality of Rincon. A 1966 USGS Quadrangle map shows the topography of the site as relatively flat.

Figure 0-6. Aerial Photograph of Rincón 2 and Approximate Waste Boundary

Field Observation Results

Rincón 2 was visited on 28 March 2011. The temperature during the site visit was 75 ^{o}F with partly cloudy skies (Wunderground 2011a). Mr. Harold Gonzalez, JCA, accompanied the project team to the site. Based on visual inspection, the site had an undulating grade throughout and was bounded on the west by the Caribbean Sea and on the east and north by residences. The southern, northern, and eastern boundary of the waste was inferred based on visual inspection.

The site did not have fencing or other means to control access – no lockable gate or signage was visible at the site upon entry. Furthermore, three homes were constructed within the landfill's footprint. The site appeared to be subject to open dumping, particularly in the southern portion of the site. It was unclear whether the materials dumped at the site was waste generated from the residences located on the landfill or if the materials came from elsewhere.

The presence and thickness of cover soil at the site varied throughout the landfill. It was unclear whether any soil cover had been installed as part of closure or compliance activities – anecdotal information from residents that live on the site indicated that any soils present were put in place by the residents and not as part of any closure activity. Beach sand covered portions of the landfill on the western edge. Exposed waste was found occasionally in areas with insufficient cover. Vegetation was established over a portion of the site but mostly appeared to be minimally controlled. Trees and bushes populated the eastern and southern portions of the site including some fruit-bearing trees located in apparent areas of buried waste. Visible waste deposits included materials that had been placed in recent years as well as layers of waste that had been placed historically as seen on the western and eastern edge of the site.

A large portion of the western edge of the site was in direct contact with the waves of the Caribbean Sea (Figure 3-7). Anecdotal information from the residents at the site suggested that the landfill historically extended further to the west but had been eroded over the years (Figure 3-8), though an estimate of how far to the west the landfill extended historically was not known. An analysis of erosion of the coastline Rincon conducted by the USGS suggested that the stretch of coastline where the landfill lies has been subject to substantial erosion with an average recession rate of 1.1 m/year (USGS 2007). Thus, it is possible that the landfill was larger and extended further west at one time. Because of the proximity of the landfill to the sea and the impact of the tides on the landfill, the western slopes of the landfill ranged from relatively flat to 1-4 ft thick vertical walls.

Figure 0-7. Eroded Western Edge of Rincón 2

Figure 0-8. Stratification of the Western Edge of Rincón 2

Leachate seeps were not witnessed directly; however, since much of the western edge of the waste is exposed to the tides, leachate (by definition) is constantly being generated and discharged into the sea. A small area of riprap was emplaced along a south-facing portion of beach. Anecdotal information gathered from residents during the site visit suggested that the riprap was placed to reduce the amount of waste washout towards the north. The riprap was mentioned in the previously-referenced US Fish and Wildlife Service e-mail and indicated that the riprap had caused further erosion in the unprotected sand beach. A ditch that ran along the eastern side of the landfill contained a liquid that appeared to be leachate, but this ditch appeared to be an area where the nearby residents discharged their wastewater, so a differentiation between potential leachate and municipal wastewater was not possible (see Figure 3-9). No leachate control systems were found at the site.

Figure 0-9. Ditch to the east of the Closed Rincón Landfill.

Objectionable odors were present at the southern portion of the site in an area that appeared to have an animal carcass as well as along portions of the eastern edge of the site where the accumulated wastewater was present. Vectors (e.g., flies) were present throughout the site.

No groundwater monitoring wells, subsurface gas monitoring probes, or stormwater management features were observed during the site visit.

Field Measurement Results

Figure 0-10 shows the site, the approximate SEM path followed at the site (solid red line), and the location on the landfill where the Guelph Permeameter test was performed (yellow dot).

No methane surface emissions were detected above background levels during the monitoring event. No evidence of a clay cover was present, but the measured hydraulic conductivity of the site soils (1.3×10^{-4} cm/s) was an order of magnitude greater than the Puerto Rico Non-Hazardous Solid Waste Management criterion of 1×10^{-5} cm/sec. Appendix C contains additional details regarding the calculation of the hydraulic conductivity of the soil at Rincón 2.

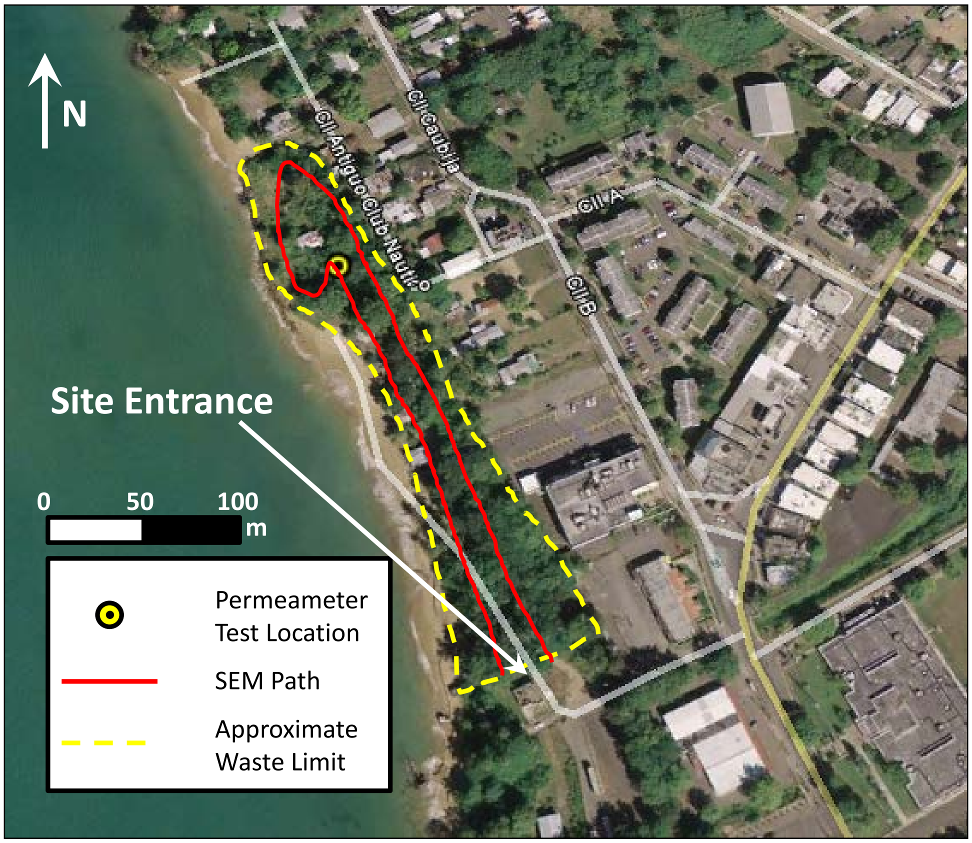

Figure 0-10. Methane Surface Emissions Monitoring Path and Guelph Permeameter Test Location at Rincón 2, Rincón, Puerto Rico

Cabo Rojo

Background Information

The Municipality of Cabo Rojo is located in southwestern Puerto Rico in Bo. Boquerón to the west of PR-301 (at approximately 18° 0'47.09"N, 67° 9'3.35"W). The landfill is adjacent to a bird sanctuary, the Refugio de Aves de Boquerón. The facility starting accepting waste in the 1970s, was ordered by the JCA to close in September 1993, and a closure plan was prepared in March 1994 (later revised in September 1994). According to the closure plan, the facility occupies approximately 10 acres and has approximately 996,000 m^3 of waste in place (Jordan, Jones, and Goulding 1994). A 1966 USGS Quadrangle map of the site shows that the site was constructed largely in a mangrove swamp at an elevation of about 1 m or less. Comparing pre-development grades on the USGS map to GPS data collected using a hand-held device during the site visit, the thickness of waste at the site ranges from about 1 to 11 m. Figure 3-11 shows an aerial photograph of the site and the approximate edge of waste based on site contours and the available historical information.

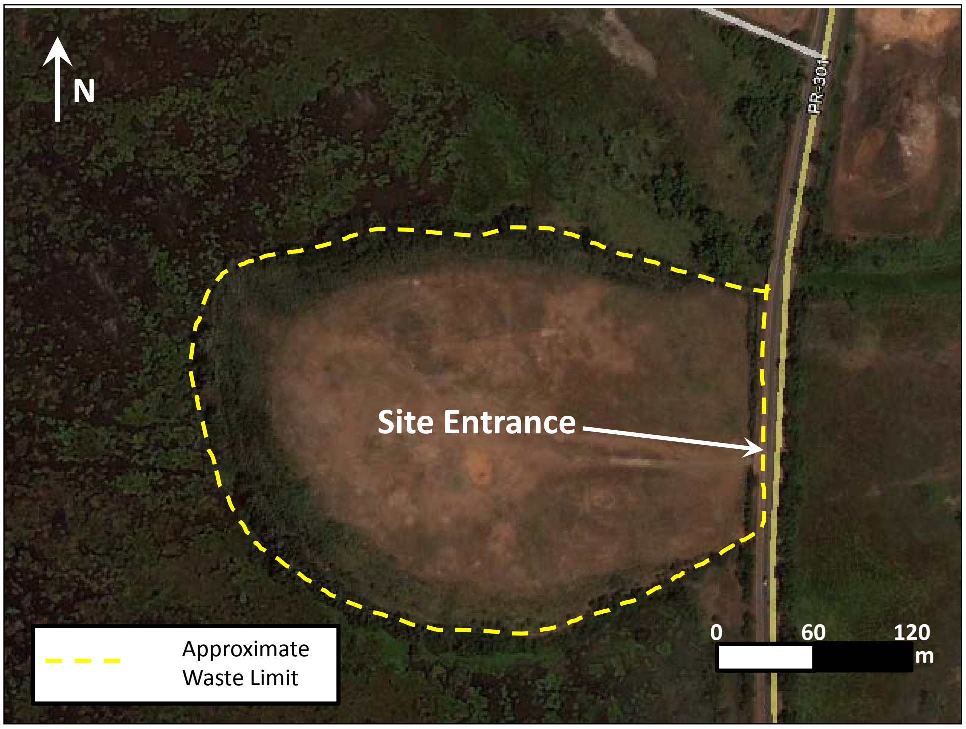

Figure 0-11. Aerial Photograph of the Closed Cabo Rojo Municipal Landfill and Approximate Waste Boundary

The closure plan called for the construction of a final cover system which included an 18-inch compacted clay layer and a soil erosion layer capable of supporting vegetative growth. The closure plan also specified the construction of several storm water control features (Jordan, Jones, and Goulding 1994). Following review of the Closure Plan in October 1994, JCA submitted a request for additional information regarding the following details that were not included in the closure plan:

Identification of the number and location of groundwater monitoring wells and subsurface gas probes.

Submission of a groundwater monitoring plan.

Submission of a subsurface gas monitoring plan.

Closure certification signed by an engineer licensed in Puerto Rico.

In 1996, JCA conducted several site inspections at the Cabo Rojo Municipal Landfill (13 June, 2 October, and 3 December). At the time of these inspections, as much as 65% of the landfill had been covered with an apparently “satisfactory” clay cover. The inspection noted that the clay thickness was estimated at 6 in. The remaining 35% of the landfill was apparently covered with compacted caliche. The thickness of this layer was estimated at 2-3 ft (JCA 1996b). In addition to the concerns regarding the cover, the inspection report also stated that the municipality needed to stabilize the west slopes and the slopes adjacent to the wildlife refuge. At the time of the June 1996 inspection, the mayor and site manager of Cabo

Rojo indicated to JCA that the municipality intended to request a waiver from the governing board to be exempt from the requirements to monitor groundwater.

The municipality submitted a hydrogeological report prepared by Jordan, Jones, and Goulding (JJG) for the site in 1996. The report made the case that groundwater monitoring at the site should not be required because of site-specific hydrogeological conditions – indicating, among other reasons, that background quality of the water was already poor and the presence of the landfill would not worsen the conditions based on literature-reported landfill leachate quality. JCA responded to the report in 1997 by disagreeing with the report's assertion that groundwater monitoring was not required and ordered that a groundwater monitoring system be installed per Chapter VII of the Puerto Rico Regulations for Non-Hazardous Solid Waste Management (JCA 1997c). JCA also noted that a waiver to the requirement to monitor and track groundwater quality can be granted if the owner/operator can prove that there is no potential for hazardous contaminants to migrate from the landfill to the aquifer during the active phase and post-closure period of the site.

Following Hurricane Hortense in 1996, a 2 October site inspection revealed that the facility had largely been unaffected by the storm, and the municipality should move forward with closure activities at the site, giving priority to the construction of a leachate collection system and a gas venting system given the proximity of the site to the wildlife refuge. Specific details regarding requirements of the leachate collection system and gas venting system were not available for review; however, JCA noted that the gas ventilation system was of particular importance given historical subsurface fires at the site (JCA 1996c).

In December 1996, JCA returned to the site for an additional inspection. Rainfall from the days leading up to the inspection had washed out some of the newly-placed cover material exposing underlying waste. The inspector noted that the site was operating in accordance with the rules at the time of the inspection (JCA 1996e).

In April 1997, JCA issued a letter to the municipality notifying them of the findings of an inspection from the previous month. At the time of the inspection, the municipality had begun installing fence posts for a perimeter fence. Vegetation had become well-established on much of the clay layer; however, many areas of the cover had eroded leaving some underlying waste exposed. In addition, leachate collection and gas venting systems had not been installed (JCA 1997a).

In September 1999, JCA sent a letter to the Municipality of Cabo Rojo notifying them of several concerns regarding the closure of the site (JCA 1999). Among the items to be addressed before the closure could be certified were:

Insufficient clay cover on some areas of the landfill.

Uncontrolled vegetative growth on the surface and side slopes.

Stabilization of all side slopes.

Construction of a stormwater control system.

Construction of a leachate collection system.

Installation of a gas ventilation system.

In the same correspondence, JCA notified the municipality that the closure plan for the facility had not addressed several requirements including:

The number and location of groundwater monitoring wells.

The number and location of explosive gas monitoring wells.

Preparation and submission of a Groundwater Sampling Plan.

Preparation and submission of an Explosive Gas Monitoring Plan.

In March 2000, the municipality sent a letter to JCA notifying them that ESA Group had been contracted to develop plans to correct the deficiencies in the closure of the site (Municipality of Cabo Rojo 2000). In the letter, the municipality stated that ESA would:

Identify the present and future design capacity of the landfill.

Develop a compliance plan for approval by JCA.

Prepare a preliminary design for a new cell at the landfill.

Prepare an operations plan for the site.

Correspondence beyond March 2000 was not available, thus the status of completing the closure activities is unknown.

Field Observation Results

The site was visited on 28 March 2011 on a partly cloudy afternoon with a strong southerly wind and a temperature of 86 ^{o}F (Wunderground 2011a). Mr. Harold Gonzalez, JCA, accompanied the project team to the site.

From the main entrance to the landfill off of PR-301, the site was fenced with chain-link fence, and signage indicating the site as a closed landfill was visible from the road (Figure 3-12). Barbed wire fencing was present on the south side of the landfill; the presence of fence along the northern and western sides could not be assessed because of dense vegetation and steep slopes that limited access to the bottom of the slope. The landfill had a relatively gentle slope upward towards the west from PR-301. An unpaved access road was present that ran toward the west from the facility’s entrance. The entrance had a gate and a lock.

Figure 0-12. Closure Signage Posted at the Closed Cabo Rojo Municipal Landfill

The site's closure plan indicates that the slopes vary in grade from 2% to 50% (or 1:1 horizontal to vertical slope ratio). The combination of heavy vegetation and steep slopes prevented a detailed visual assessment of the west and north side slopes and limited assessment of the southern slope (Figure 3-13). Historical reports indicate that slope stabilization was an issue in the past; however, because the side slopes were generally inaccessible during the site visit, the degree of slope stabilization could not be assessed.

No groundwater monitoring wells were observed at the site, nor were gas monitoring wells. Additionally, evidence of leachate controls or storage was not observed. A stormwater ditch was present along the main road to the east of the landfill but it was unclear if this feature was constructed as part of the landfill's closure activities, had naturally formed over time, or built as part of constructing PR-301. Other than this stormwater ditch, no other stormwater control features were visible.

From visual inspection, the cover appeared to be a sandy clay. Exposed garbage was visible in one isolated area. The majority of the accessible portion of the landfill had established vegetation; however, the vegetated areas were scattered amongst barren areas. The side slopes also held mature, uncontrolled vegetation including large bushes, tall cotton plants, and other shrubs. No leachate seeps were found on the accessible portions of the landfill. No recent waste deposits were found at the site, and no objectionable odors or vectors were apparent on the landfill surface or accessible side slopes.

Figure 0-13. Vegetation on the Side Slopes at the Cabo Rojo Municipal Landfill

Field Measurement Results

Figure 0-14 shows the approximate path taken during SEM measurements and the location of the hydraulic conductivity test performed at the site. SEM readings were taken around the top deck and eastern side slope – as described earlier, the northern, western, and southern slopes were steep and densely vegetated and thus were excluded from the monitoring path. Fort the most part, methane was not detected above background levels, but two areas on the southwest portion of the landfill's top deck exhibited concentrations of up to 10 ppm.

It took several attempts for the project team to obtain a hydraulic conductivity reading since the first three test holes advanced had rocks and other debris present, thus disallowing the auger from reaching the appropriate depth. The field test was ultimately conducted on the fourth borehole that was advanced. Visual classification of the soil indicated it was clayey with some silt. The measured hydraulic conductivity of the final cover soil was then measured to be 4.4×10^{-6} cm/sec. See Appendix D for the calculation of the hydraulic conductivity of the final cover soil at Cabo Rojo.

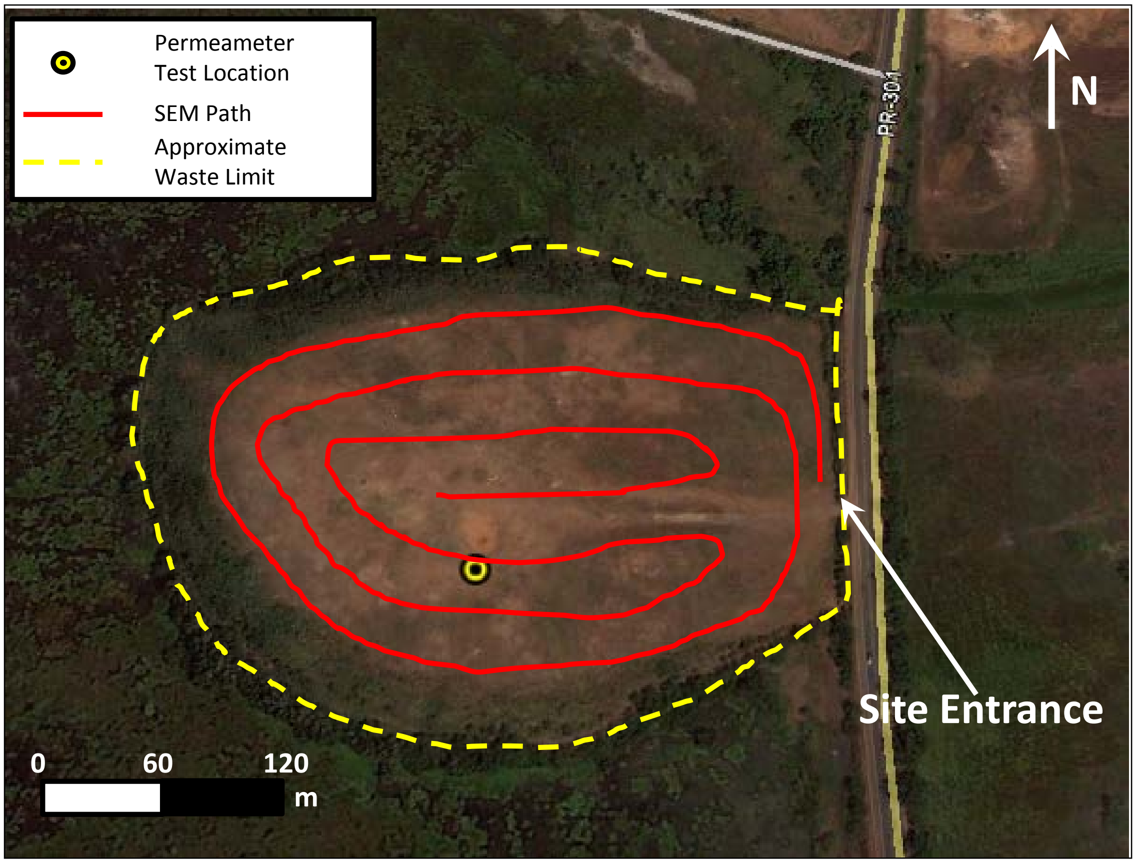

Figure 0-14. Aerial Photograph of the Closed Cabo Rojo Municipal Landfill with Approximate Waste Boundary, Surface Emissions Monitoring Path, and Hydraulic Conductivity Measurement Location

Vieques

Background Information

The island of Vieques is located off the east coast of mainland Puerto Rico. The closed Vieques landfill site occupies approximately 10 acres on the northern coast of the island off of PR-200 (at approximately 18° 9'29.26"N, 65°25'38.72"W). Limited historical information on the site was available, but anecdotal information suggests that municipal waste generated from the Municipality of Vieques as well as from nearby US Navy installations was disposed at the site. GPS measurements taken at the site indicated site elevations ranging from 3.9 m to 7.7 m. Figure 0-15 shows an aerial photograph of the site and the inferred waste limits as estimated from anecdotal information provided by those assisting the project team at the site and the conditions encountered in the field.

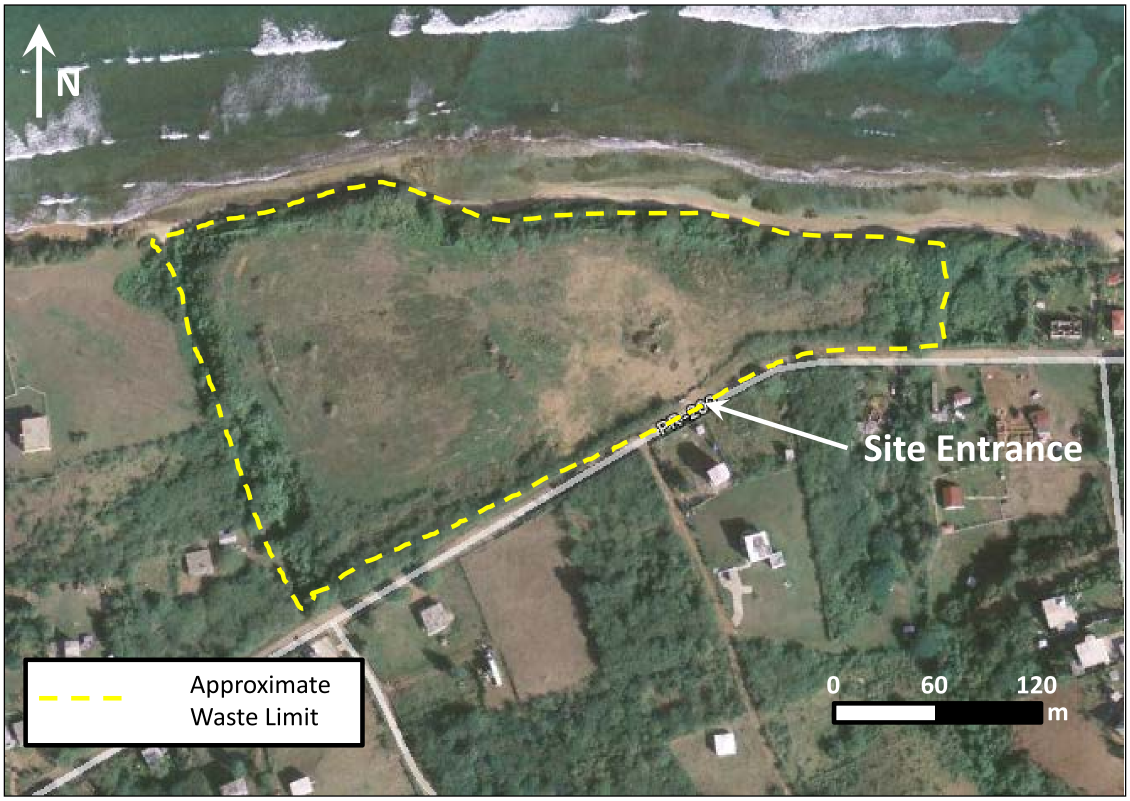

Figure 0-15. Aerial Photograph of the Closed Vieques Landfill and Approximate Waste Boundary

Field Observation Results

The field team visited the closed Vieques Landfill on 29 March 2011 on an 84 ^{o}F day with scattered cloud cover and moderate winds (Wunderground 2011b). Vieques Island was accessed by taking a passenger ferry from Fajardo and the project team was escorted to the site by Mr. Danny Rodriguez (US EPA Caribbean Division) and Mr. William Cruz (Municipality of Vieques). Ms. Myrna Ríos of JCA also accompanied the project team to the site.

The site was elevated from the adjacent beach. A chain link fence was found around most of the site; barbed wire fence was found along the northern slope adjacent to the beach. Much of the fence line had been torn down or was sagging (Figure 3-16). The facility's main entrance did not have a locking gate – at the time of the field visit a 3-ft high soil berm was in place to prevent vehicle access. A large sign at the entrance provided the name of the landfill and indicated that the site was closed.

Figure 0-16. Sagging Fence at the Closed Vieques Landfill

The landfill was mostly flat and predominantly level. The northern slope could not be accessed so it is unknown whether this portion of the landfill had a gradual or steep slope. A small herd of horses was grazing within the landfill's limits along with several trails (Figure 3-17), small pits that appeared to be dug by an animals (or humans to collect water for animals) as well as manure were found throughout the site. No leachate seeps were visible at the site.

Vegetation consisting of grasses, shrubs, and trees was present throughout the site but was not uniform in appearance and much of the vegetation appeared to be dead or dying (note that less than 0.5 in. of rain fell in the month preceding the site visit (Wunderground 2011b)). Isolated areas of the landfill surface showed evidence of previous, small fires at the site. It was unclear whether or not the fires were set deliberately. A variety of grasses, shrubs, and small trees were found throughout the site.

The soil at the site was a silty sand based on visual inspection. The cover thickness was variable throughout the site – exposed waste was present in several areas of the site. The landfill surface also exhibited minor undulations and surface depressions which following rainstorms likely hold water. Additionally, various pieces of debris were present in small amounts throughout the site, though it was not clear whether this material was deposited at the site before or after the landfill ceased operations. No objectionable odors or vectors were apparent at the site.

Figure 0-17. Herd of Horses Grazing at the Closed Vieques Landfill

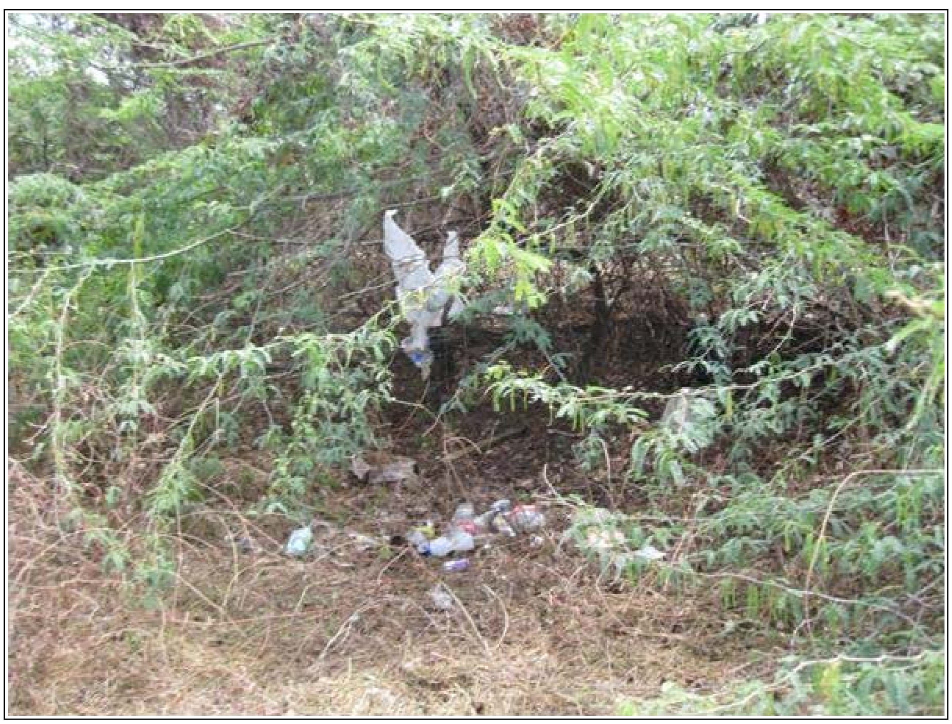

Figure 0-18. Recent Waste Deposits at the Closed Vieques Landfill

No groundwater monitoring, subsurface gas monitoring, stormwater control, or leachate control systems were observed at the site.

Field Measurement Results

Figure 3-19 shows the approximate SEM path followed (solid red line) and the location of the Guelph Permeameter test performed at the Vieques Landfill (yellow dot).

During surface emissions monitoring, methane was detected on a limited basis. A few detections greater than background readings were measured, but no measured concentration exceeded 10 ppm during the sampling period. Since access to the north edge of the landfill was limited, methane surface emission readings were limited to the top deck of the landfill.

The data collected with the Guelph Permeameter was used to calculate a hydraulic conductivity of 9.0 x 10^{-5} cm/s. Additional details on the calculation of the hydraulic conductivity of the cover soil at the site are provided in Appendix E.

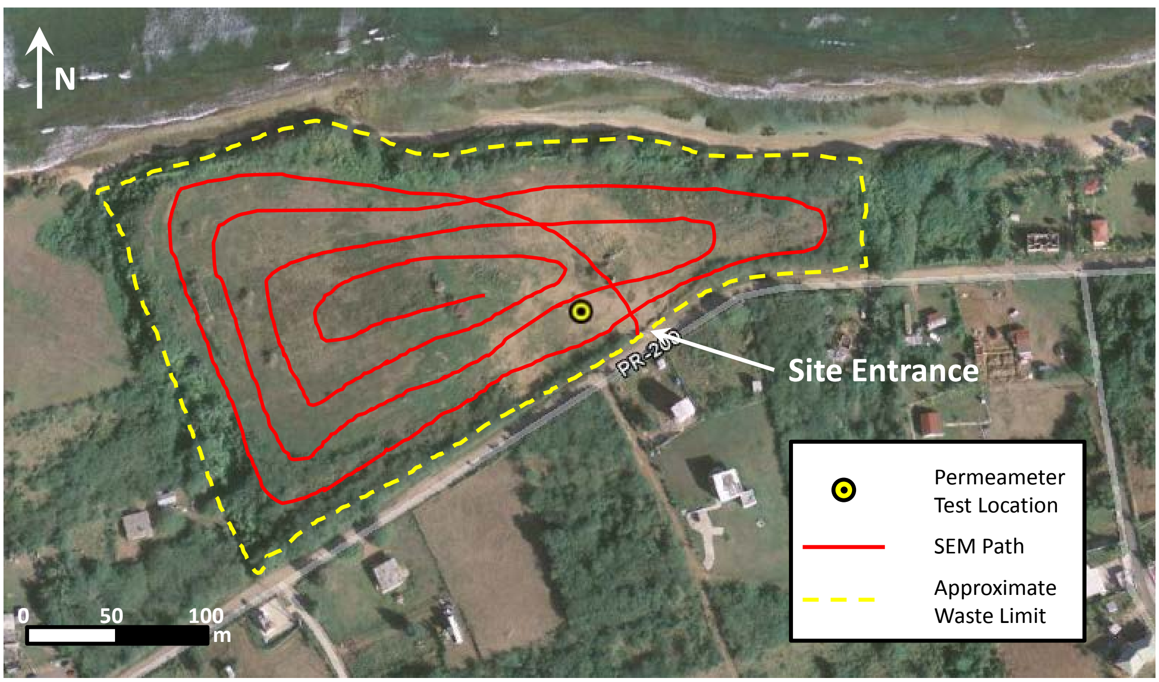

Figure 0-19. Surface Emissions Monitoring Path and Guelph Permeameter Test Location at the Closed Vieques Landfill, Vieques, Puerto Rico

Discussion and Recommendations

Discussion

RCRA Subtitle D and the Puerto Rico Non-Hazardous Solid Waste Management rules require MSW landfills to be closed in a manner that minimizes the impact on human health and the environment and return the land to beneficial reuse. The regulations aim to reduce the transport of potentially harmful gases and liquid contaminants beyond the perimeter of the site and to physically stabilize the landfill.

Table 4-1 lists the metrics used to evaluate each site and the result of the observation of each metric for each site. The criteria can be broadly classified in five major categories:

Access Control,

Environmental Monitoring and Control Systems,

Maintenance,

Waste Mass Stability, and

Final Cover

Each criterion is described further in the following sections.

Table 0-1. Summary of Visual Assessment Criteria

Criterion	Rincón 1	Rincón 2	Cabo Rojo	Vieques
Access Control				
Complete Accessibility	No	No	No	No
Fence	Partial[1]	No	Yes[1]	Partial
Gate	Yes	No	Yes	No
Lock	NA	No	Yes	No
Recently-Placed Waste	Yes	Yes	No	Yes
Signage	Yes	No	Yes	Yes
Non-Vector Animals	No	No	No	Yes
Environmental Monitoring and Control Systems				
Groundwater Monitoring Wells	Yes[2]	No	No	No
Subsurface Gas Monitoring Probes	Yes[2]	No	No	No
Leachate Control	No	No	No	No
Stormwater Control	No	No	Yes[3]	No
Maintenance				
Exposed Waste	No	Yes	Yes	Yes
Leachate seeps	No[1]	Yes	No[1]	No[1]
Vegetation	Inadequate[4]	Inadequate	Overgrown	Inadequate[5]
Odor	No	Yes	No	No

Criterion	Rincón 1	Rincón 2	Cabo Rojo	Vieques
Vectors	No	Yes[6]	No	No
Waste Mass Stability				
Potential unstable slopes[7]	Yes	Yes	Yes	NA[1]
Final Cover				
Hydraulic conductivity < 10^{-5} cm/sec	NM	No	Yes	No

NA = Not available NM = Not measured

1 The criterion was not assessed for the entire landfill since some portions of the site were inaccessible.

2. Historical documents confirm that wells were installed at the site; however, the project team did not witness them while in the field.

3 A ditch parallel to the main road was adjacent to the landfill; however, it is not clear if the ditch was intentionally constructed as part of landfill closure or for stormwater conveyance as part of the road construction, or if the ditch had formed naturally.

4 Large areas (on the order of acres) of the Rincón Municipal Landfill lacked vegetative cover.

5 Vegetation was difficult to assess as a result of an ongoing drought in the region. Some areas exhibited dense vegetative growth; however, many areas of the landfill held sparse vegetation, and the earthen cover was more prominent.

6 Flies were present throughout the site.

7 Slope stability was assessed based on visual observations in the field regarding the steepness of the slopes and other environmental factors (e.g. contact of tides with slopes).

Access Control

Preventing public access to closed landfills helps to secure closed landfill sites from unauthorized access. 40 CFR 258.25 requires all MSW landfill units to prevent public access, vehicular traffic, and illegal dumping through the use of artificial and/or natural barriers. Fences, gates, and locks all contribute to preventing unauthorized dumping, scavenging, or other illicit activities.

Fences can also prevent site access by animals and other livestock. Free-roaming livestock and other animals are prevalent in many parts of Puerto Rico. Allowing free-grazing animals at closed landfills can potentially lead to damage to cover systems or environmental monitoring and control systems. For example, at the Vieques Landfill, minor undulations in the cover appeared to have been created by the horses grazing on the landfill. Given that final covers are constructed, in part, to minimize infiltration of precipitation, such depressions can promote water retention thereby increasing the potential for leachate generation. Livestock manure may also attract vectors.

Environmental Monitoring and Control Systems

Groundwater and gas monitoring systems are useful for evaluating the impact of a landfill site on human health and the environment as part of long-term care activities. With the exception of Rincón 1, no facilities appeared to have any environmental monitoring systems in place (note that presence of groundwater wells at Rincón 1 were reported in historical documentation but were not observed by the field team during the site visit since knowledge of these wells came after the site visits were completed). No gas or groundwater monitoring data was available for review from any of the visited sites.

Environmental control systems also play an important role in maintaining the integrity of a closure system. No facilities were found to have leachate control or stormwater control systems. Stormwater control infrastructure prevents the loss of final cover soil via erosion, controls and directs runoff to appropriate management areas, and can reduce failure of final cover systems by reducing erosive forces. Stormwater control systems also reduce the potential volume of leachate generated by minimizing percolation of rainfall into the waste mass. Several of the facilities had large, relatively flat areas which did not appear to route stormwater away from the waste mass, but rather appeared to promote surface ponding.

Historical documents suggest that JCA required Cabo Rojo and Rincón 1 to install leachate control systems. The circumstances surrounding the requirement to install such systems are unknown. The presence of leachate seeps on the side slopes at both sites could not be evaluated because of steep slopes and heavy vegetation.

Historical documents indicate that Cabo Rojo had also been instructed to install a system to vent gases from the landfill. The details surrounding the request to install a gas venting system are unclear. No evidence of a gas venting system was seen during the site visit. A June 1996 closure inspection report by JCA indicated that nine gas monitoring wells had been installed. Although the locations of these wells were not shown in a plan view, they appeared to be installed near the edge of the waste and mostly on the top deck of the landfill. No evidence of these wells was observed during the site visits.

Maintenance

Routine monitoring and maintenance of the cover, vegetative growth, access control infrastructure, and environmental monitoring and control infrastructure is required to ensure the integrity of the closure system at MSW landfills. The Cabo Rojo Municipal Landfill, the Vieques Landfill, and Rincón 1 each, to some degree, appeared to require mowing or other forms of vegetation maintenance. At Cabo Rojo, three of the four side slopes were overgrown which contributed to the inaccessibility of the site. Similarly, at Rincón 1, vegetation along the north slope (in conjunction with steep slopes) made access to the north slope unsafe.

Fences should be maintained to prevent public access. At Vieques, the fence on the north side of the site was found to be sagging (as illustrated in Figure 3-16) or completely down in some instances. Maintenance of access roads and vegetative growth also facilitates access to monitoring infrastructure, where present. Historical documents for Rincón 1 indicate that maintenance of the existing groundwater wells was previously requested in an inspection report.

Maintenance of the final cover system also prevents rainwater percolation to the waste layer and minimizes odors and vector attraction. Exposed waste was found at Vieques, Cabo Rojo, Rincón 1, and Rincón 2.

Waste Mass Stability

Waste mass stability was visually evaluated at each site—the field team looked for steep slopes, evidence of side slope failure, and other factors that may affect the stability of the waste mass. No evidence of previous slope failure was witnessed while in the field, though it is noted that the majority of the toe of the slope at two of the sites (Rincón 1, Cabo Rojo) as well as the northern slope face at Vieques, was not accessible. Furthermore, heavy vegetation in some areas precluded accurate identification of slope failure. A closure inspection report for one of the sites (Cabo Rojo) indicated that some form of slope stabilization had been conducted as part of closure activities, but further details were not available. Steep slopes (greater than the standard 3 horizontal to 1 vertical for above-grade landfill slopes) were present at all four sites that were visited.

Other factors were observed in the field that may contribute to long-term waste mass instability. For instance, the proximity of Rincón 2 leaves it subject to the rising and falling tides of the Caribbean Sea. Exposed waste on the western edge of Rincón 2 was in direct contact with the sea during the site visit. A coastline recession study conducted by the USGS in 2007 suggests that the shoreline in this area has recessed at a rate of 1.1 m/yr. Thus, it is likely that a potentially substantial portion of the landfill has already been washed away into the sea, and projections from the USGS (2007) report suggest the shoreline (and thus the western boundary of the landfill) will continue eroding absent of shoreline stabilization measures. Although a shoreline analysis in Vieques similar to that of Rincón was not available, the northern edge of the Vieques Landfill was located near the shoreline and could be subject to similar tidal contact and influence.

Final Cover

The final cover system of a closed landfill plays a critical role in reducing the environmental impact of the site. Chapter 40 CFR 258.60(a) and Puerto Rico Non-Hazardous Solid Waste Management Rule 565(A) requires that the permeability of the final cover soil be less than or equal to the permeability of any bottom liner system or natural subsoils present or less than or equal to 1×10^{-5} cm/sec, whichever is less. Furthermore, the regulations each require that a 6-in erosion layer of earthen material capable of supporting vegetative growth be placed over an 18-in infiltration layer of compacted earthen material that meets the permeability requirement.

During the field experimentation, a single hydraulic conductivity measurement was taken on location at three sites. The intent of these measurements was to conduct a fairly rapid field measurement for comparison to the regulatory metric – results of a single measurement cannot be extrapolated across the entire landfill, but can provide an indication whether site soils present may include some areas with (or without) a low-permeability layer.

The permeameter apparatus and experimental procedure has limitations in that the one-head test method (used at all three sites) is accurate between 10^{-2} to 10^{-5} cm/sec and only within a factor of two. Because the hydraulic conductivity was calculated from the data collected in the field, selecting different values for variables in the equations (e.g. values corresponding to the soil classification according to the user's manual) can have an impact on the calculated result. Detailed information on hydraulic conductivity would require a more robust field and/or laboratory sampling and analysis protocol which was beyond the scope of this study.

The hydraulic conductivity measured in the cover soil at the Cabo Rojo Municipal Landfill was less than that required in the regulations (i.e., hydraulic conductivity was less than 10^{-5} cm/sec). The measured hydraulic conductivity at Rincón 2 and Vieques was greater than that required in the regulations (i.e., hydraulic conductivity was greater than 10^{-5} cm/sec).

Recommendations

The intent of this study was to evaluate a subset of closed landfills in Puerto Rico to help guide decision-making for future MSW landfill closures on the island. During the field effort, a single measurement of the hydraulic conductivity of the final cover was taken at three sites and no environmental monitoring data were available to assist in the evaluation of the performance of the closure systems. Additionally, the inaccessibility of some areas at each site leaves some questions unanswered (e.g. presence of leachate seeps and slope failures). Notwithstanding the limitations of this study, the following sections discuss recommendations for future closures as well as recommendations for further study to help improve future closures.

Recommendations to Further Investigate Targeted Sites

The following recommendations are offered to further investigate the targeted closed landfills from this study. Broader recommendations that cover all closed landfills (and, in some cases, operating landfills that may be closed in the future) are provided in Section 4.2.2.

More Detailed Final Cover Analysis. Additional hydraulic conductivity analysis in soil covers would provide a more expansive data set so that stronger conclusions can be drawn regarding the apparent conformance of final cover installations to applicable regulations can be made. Furthermore, an evaluation of in-place soil thicknesses (to assess whether the regulatory-required 18-inch clay layer and 6-inch thick vegetative layer is present) may provide further understanding of the presence of conforming final covers.

Groundwater Evaluation. The groundwater quality at each of the targeted sites is unknown – only one of the four sites apparently had groundwater monitoring wells installed and of those two wells, two were reportedly "dry" based on a JCA inspection of the site. An assessment of groundwater quality upgradient and downgradient of each site (by taking grab samples in temporary wells (installed using a direct-push technology rig) may provide a valuable snapshot indicating potential groundwater impacts and whether additional assessment may be warranted. Analysis of field parameters (pH, temperature, dissolved oxygen, oxidation reduction potential) and laboratory parameters for collected samples (e.g., those listed in Appendix I to 40 CFR 258) would provide a substantial insight into each landfill's environmental impact. More detailed planning would be required to ensure samples collected were representative of groundwater conditions and appropriately captured potential landfill impacts – as described earlier, the complex configuration of some of the sites (e.g., Rincón 2 situated between the sea and a wastewater drainage ditch) may not make access or accurate assessment feasible.

Landfill Gas Migration Monitoring. Although methane surface emissions were evaluated at each site during this investigation, landfill gas generated within landfills tends to migrate along the path of least resistance which may not necessarily be through the top cap. Assessment of gas migration via monitoring probes at the target sites could provide information regarding landfill gas producing activity within the site and help characterize potential risk to nearby receptors. Similar to that described above with groundwater monitoring, the complex configuration of the targeted sites necessitates additional, more detailed planning to ensure that any gas migration assessment would be captured by traditional means such as screened PVC wells around the landfill perimeter. Perimeter landfill gas monitoring may be supplemented by assessing landfill gas production or concentrations within the waste itself.

Assessment of Beneficial Use and/or Remedial Opportunities. Each of the sites visited in this study had limited or no ongoing beneficial uses (e.g., recreation areas, etc.). Although assessing potential environmental impacts further is warranted, a concurrent evaluation of potential beneficial uses could serve the purpose of mitigating environmental impacts while creating useful space or a useful asset out of each of the landfills. Beneficial use opportunities could include implementation of a renewable energy project (e.g., solar panels or landfill gas beneficial use), or redevelopment of the site for public use.

Remedial opportunities should only be explored after environmental risks to groundwater, surrounding site soils, and air have been properly characterized. Following characterization, potential remedial opportunities can be identified. Low-cost, low-maintenance opportunities should be primary considerations. Given the apparent lack of covers seen at each site, one of the targeted sites may be a candidate to explore implement an evapotranspiration cover. An evaluation of evapotranspiration covers by the US EPA suggested that several areas within the Mayagüez and San Germán eco-zones (which includes Rincón and Cabo Rojo) could feasibly implement an evapotranspiration cover based on literature-reported values. A site-specific design and performance evaluation would help guide decision-making in this respect to reveal whether or not technical and economic feasibility of this technology would exist for the target sites.

Recommendations for Future Closures

Install and maintain access control infrastructure at all MSW landfills. Access control is important to help preserve the integrity of a closed landfill. Fences, gates, and locks should be installed and used where natural barriers do not already reasonably prevent access. These barriers help to prevent scavenging, illegal dumping, and unwanted habitation by local livestock.

Install and maintain the minimum-required final cover or consider alternative, performance-based final cover systems. All sites should be closed in accordance with 40

CFR 258.60(a) and Puerto Rico Non-Hazardous Solid Waste Management rules which require an 18-in infiltration layer of earthen material and a 6-in erosion layer of earthen material capable of supporting vegetative growth. The minimum permeability of the cover should be less than or equal to 1×10^{-5} cm/sec in cases where a bottom liner system is not present.

Alternative, performance-based final cover systems (such as those that rely on evapotranspiration principles) may be appropriate in certain areas of Puerto Rico. Since some landfills in Puerto Rico recently have been expanded to include bottom liner systems (thus resulting in a potentially more stringent final cover requirement based on a direct interpretation of RCRA), the importance of evaluating appropriate final cover options that are effective and can feasibly be implemented increases going forward. We recommend the implementation of a test site at a landfill located in one of the eco-zones that were identified as potentially compatible with an evapotranspiration cover in a companion project that was conducted in Puerto Rico in 2010 by US EPA ORD titled Screening Tool for Assessing Feasibility of ET Covers for Landfills in Puerto Rico.

Design and construct above-grade side slopes to a maximum 3:1 (H:V). Steep slopes may pose long-term stability issues and may make access during routine post-closure monitoring difficult. Standard landfill engineering practice is to grade side slopes to a maximum 3 horizontal to 1 vertical, though site-specific geotechnical considerations must be considered as part of any closure design. Slope stability of existing landfills should be evaluated on a case-by-case basis, and remedial actions including re-grading and slope stabilization efforts should be pursued where necessary.

Design and install stormwater management infrastructure. Stormwater benches, swales, and downchutes will help encourage run-off and prevent damage to the final cover at closed landfills. Unmanaged stormwater can have a detrimental effect to the longevity of a closed landfill. The need for stormwater retention ponds in a stormwater management system should be evaluted on a case by case basis. Additionally, each facility should apply for appropriate permits for discharging stormwater.

Maintain existing gas collection infrastructure. At sites where gas collection and control systems have been installed, the systems should be operated and maintained in accordance with Operational Standards for Collection and Control Systems (40 CFR 60.753). Annual reports should be submitted in accordance with 40 CFR 60.757(f). Routine monitoring requirements in the regulations are stringent and include operating parameters that can change fairly rapidly – effective design, construction quality assurance, and operations monitoring is necessary for future closed facilities with gas collection systems to remain in compliance.

Monitor groundwater and perimeter gas. A groundwater monitoring system should be installed and utilized in accordance with 40 CFR 258 Subpart E. Explosive gas monitoring should be conducted in accordance with 40 CFR 258.23.

Construction and Long-term Maintenance of Leachate Collection Systems. According to 40 CFR 258.61(a)(2), during the post-closure care period, leachate collection systems employed at each site must be operated to maintain a liquid head of 30 cm or less above the liner in accordance with 40 CFR 258.40. Though none of the facilities targeted in this study had leachate collection systems, a handful of facilities on the island have installed one or more lined cells with leachate collection. Monitoring and maintenance of leachate collection systems (as well as overall leachate treatment) is required for closed landfills with such systems in place. In addition to leachate collection systems associated with bottom liners, leachate interception systems may be applicable as part of closure for future facilities to ensure migration of leachate from unlined areas does not occur beyond the landfill footprint.

Limited information is available regarding the quality of leachate that is collected at active landfill sites in Puerto Rico, as well as leachate quality at sites that are closed (i.e., seeps). A comprehensive assessment of leachate quality and management practices would be greatly beneficial for Puerto Rico environmental regulators and landfill owners/operators. Given the limited experience on the island with leachate management, such a study could help provide guidance on effective leachate management techniques that are compatible with the specific challenges in Puerto Rico (e.g., climatic conditions, typical cover soil application practices, availability and proximity of wastewater treatment facilities).

Assessment of Beneficial Use Options for Other Closed Landfills or Landfills that will be Closed in the Near Future. A feasibility assessment of potential beneficial uses of closed or soon-to-be closed landfills may provide relevant information to local regulatory agencies and landfill owners and operators. Beneficial uses would likely focus on redevelopment opportunities for landfills or integration of renewable energy (such as solar panels or landfill gas-to-energy).

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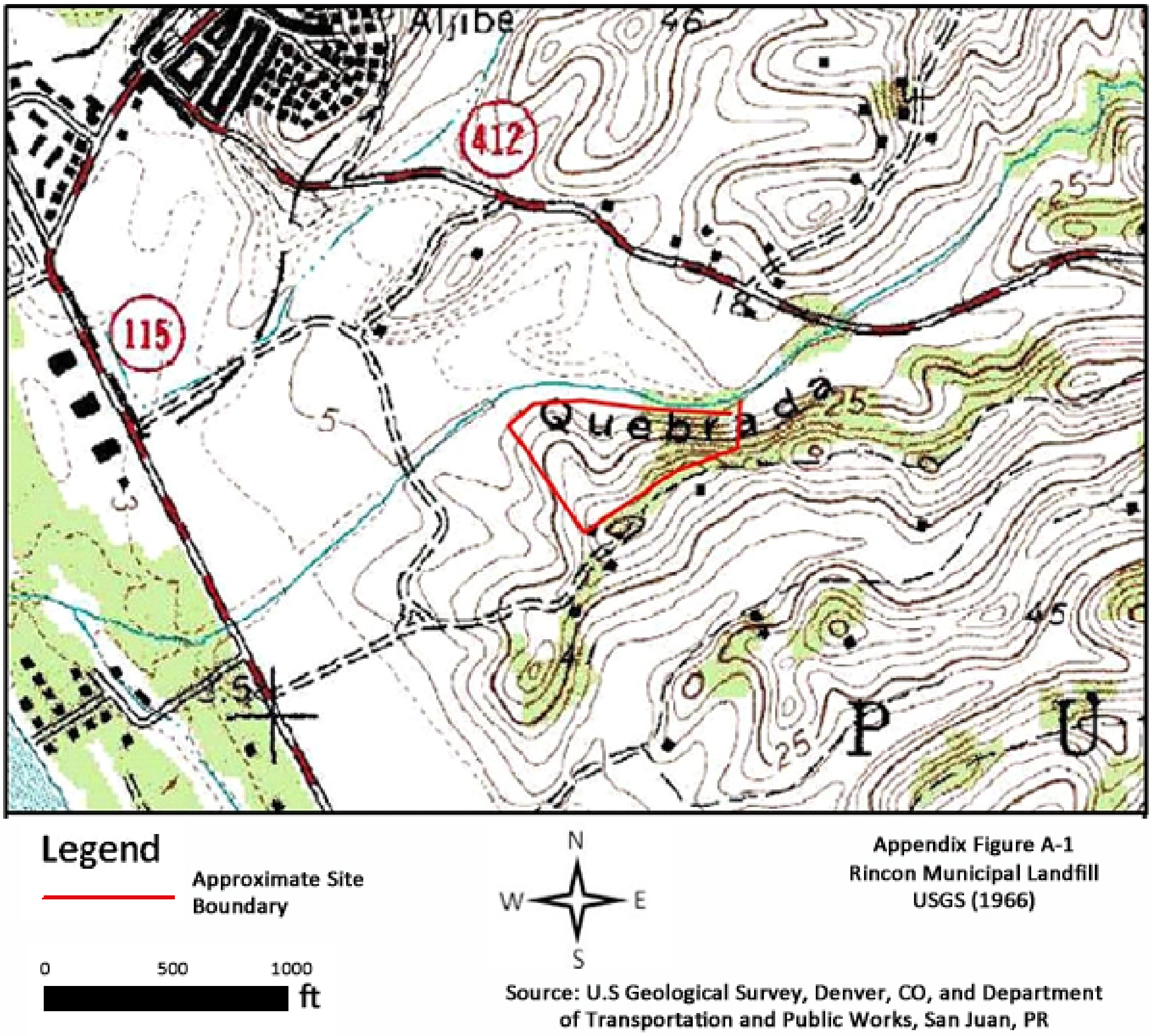
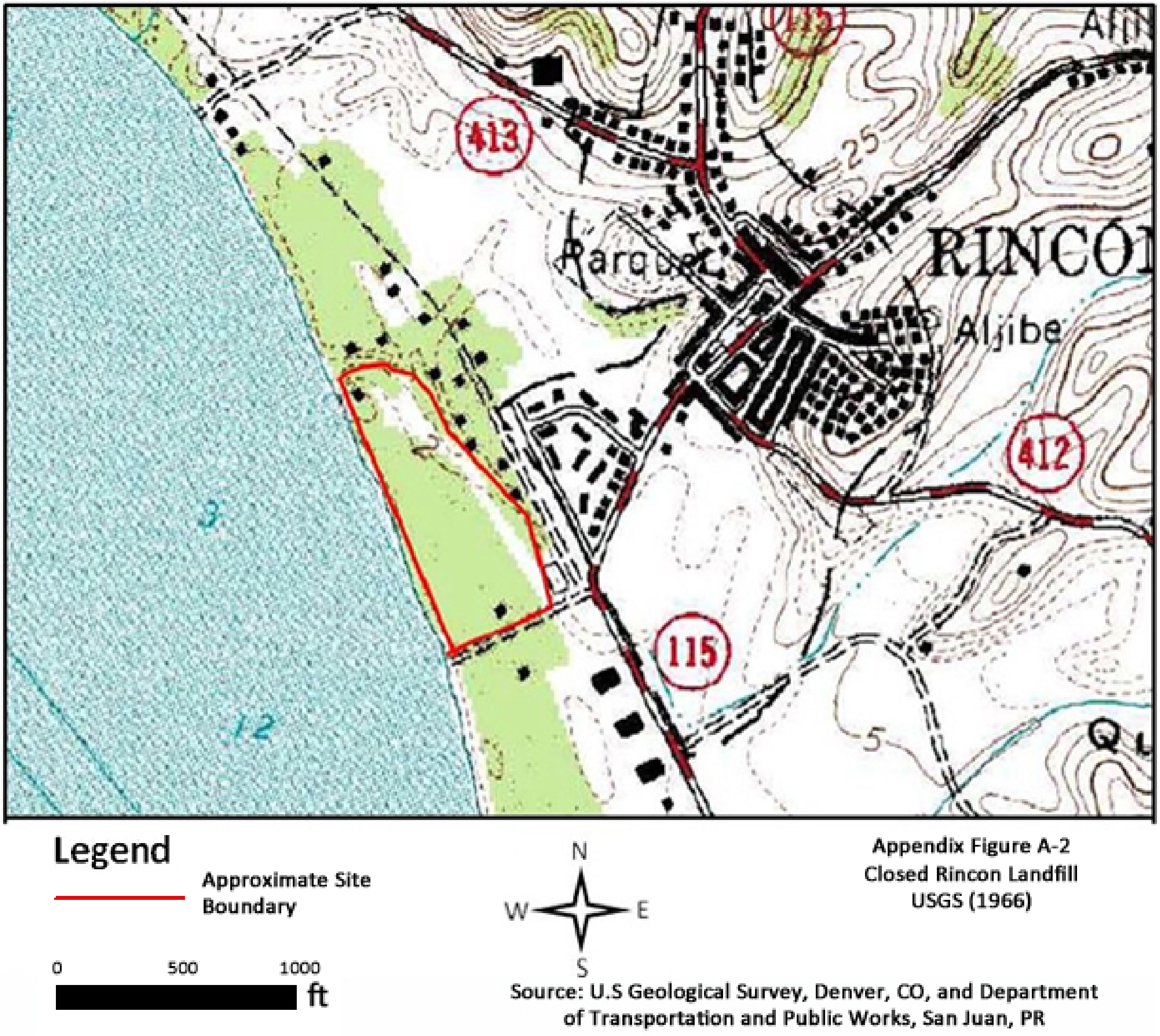
Appendix A – USGS Quadrangle Maps and Approximate Site Boundaries



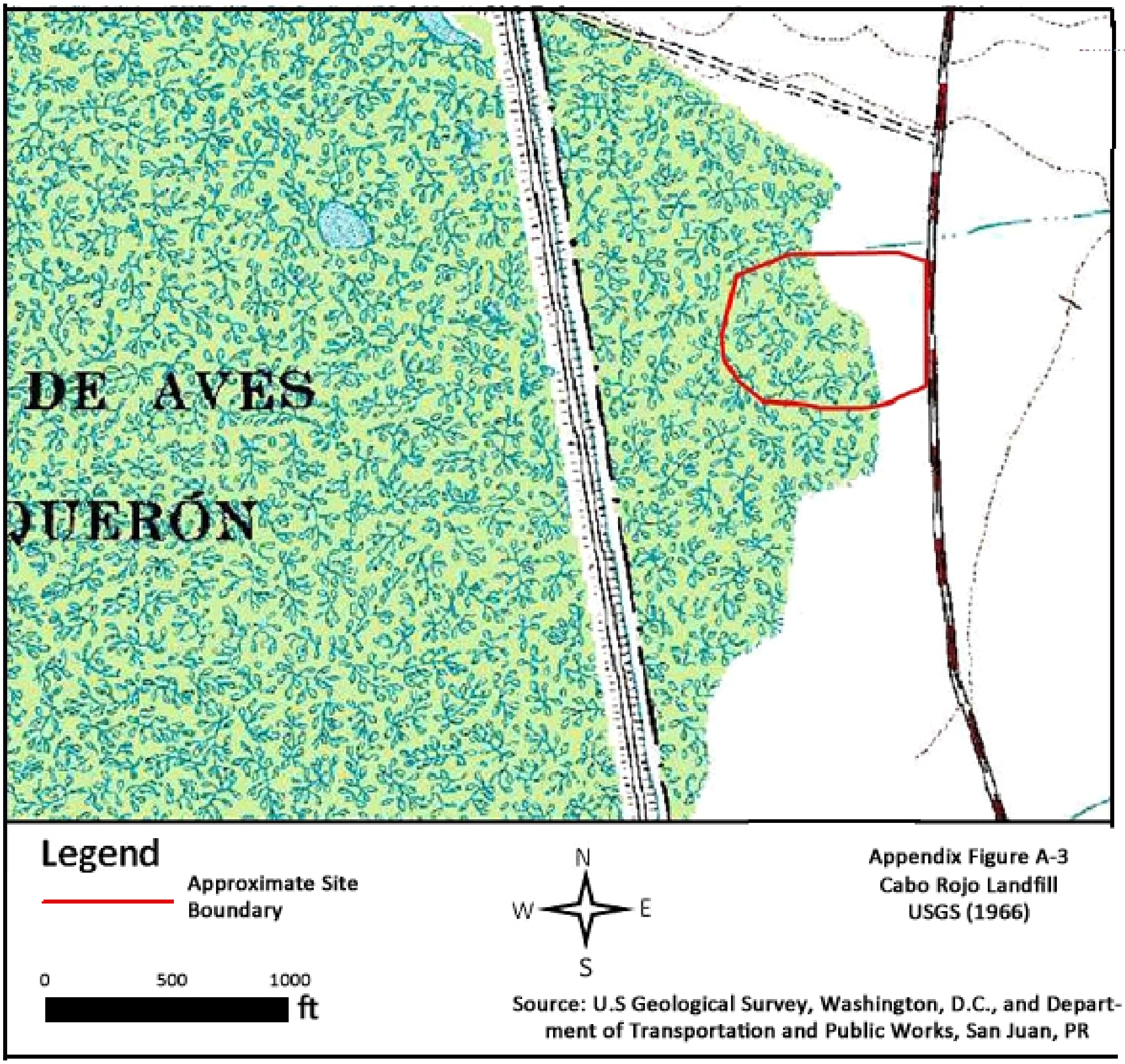
Appendix Figure A-1
Rincon Municipal Landfill
USGS (1966)

Source: U.S Geological Survey, Denver, CO, and Department of Transportation and Public Works, San Juan, PR



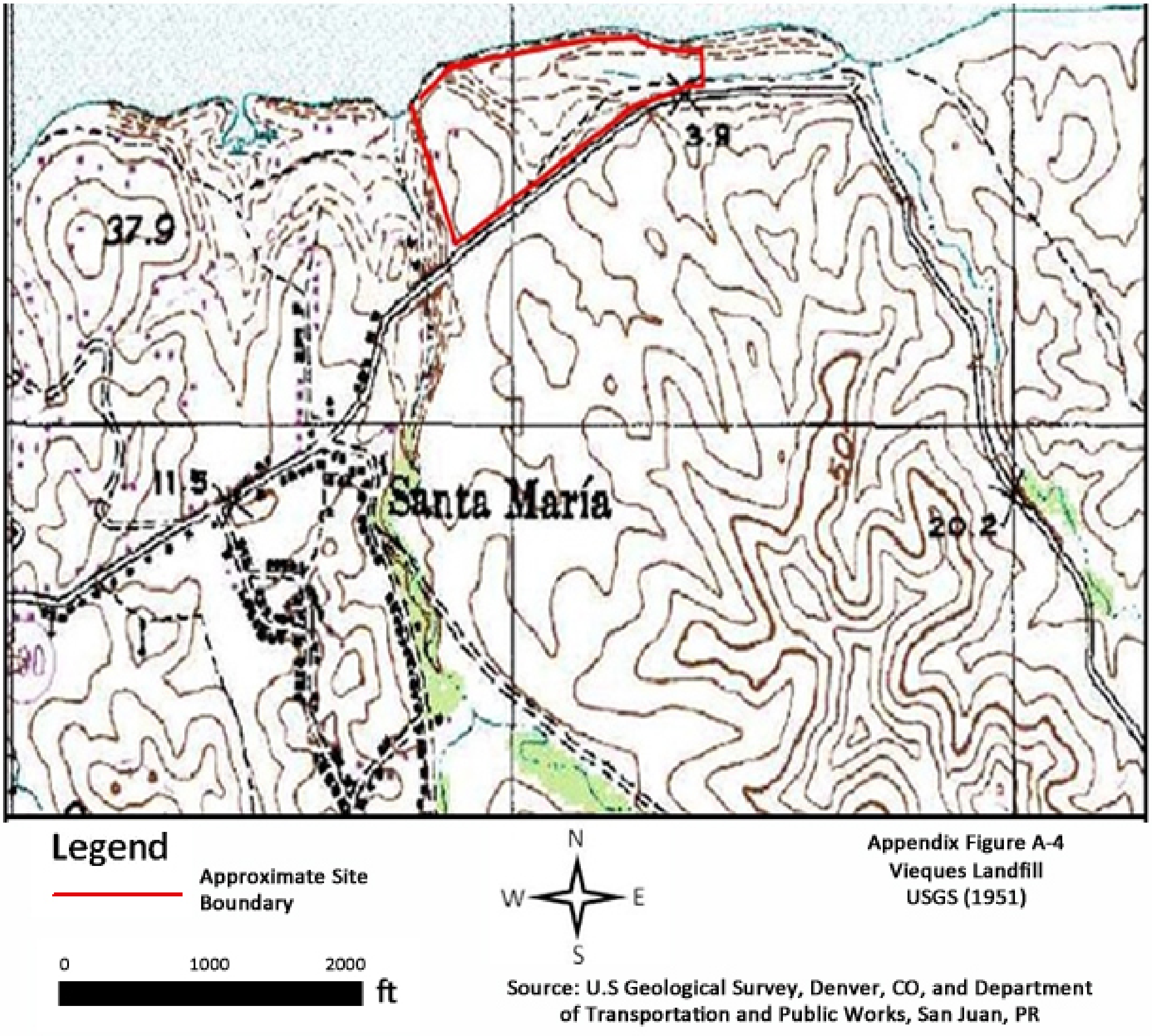
Appendix Figure A-2
Closed Rincon Landfill
USGS (1966)

Source: U.S Geological Survey, Denver, CO, and Department of Transportation and Public Works, San Juan, PR



Appendix Figure A-3
Cabo Rojo Landfill
USGS (1966)

Source: U.S Geological Survey, Washington, D.C., and Department of Transportation and Public Works, San Juan, PR



Appendix Figure A-4
Vieques Landfill
USGS (1951)

Source: U.S Geological Survey, Denver, CO, and Department of Transportation and Public Works, San Juan, PR

Appendix B – Supplemental Photographs

Photo #: Rincon Landfill 1-1

View to the east and the southern edge of the site

Photo #: Rincon Landfill 1-2

View to the north- northeast. Pile of mulch shown in the mid-ground.

Photo #: Rincon Landfill 1-3

Unknown building near the site entrance

Photo #: Rincon Landfill 1-4

Stockpile of plastic bottles at the southern edge of the site

Photo #: Rincon Landfill 1-5	Description
	Close-up view of ground mulch which was placed on much of the site’s surface
Photo #: Rincon Landfill 1-6	Description
	View of slope on the edge of the property

Photo #: Rincon Landfill 1-7	Description
	View of vegetative debris and bags with municipal waste towards the northern portion of the site. Visual inspection of the bags suggested they were placed at the site in the past few years.
Photo #: Rincon Landfill 1-8	Description
	View downslope towards the eastern portion of the site

Photo #: Rincon Landfill 1-9	Description
	Stockpile of intact and broken cathode ray tubes that were placed in a trailer
Photo #: Rincon Landfill 1-10	Description
	Tank that was present on the southern portion of the site. The use and contents of the tank could not be determined during the site visit.

Photo #: Rincon Landfill 1-11	Description
	Enclosures at plant nursery on site
Photo #: Rincon Landfill 1-12	Description
	Mobile equipment staged on site.

Photo #: Rincon Landfill 1-13	Description
	Municipality collection vehicle that arrived to pick up the plastic bottles from the stockpile.

<table>
<tr><td>Photo #: Rincon Landfill 2-1</td><td>Description</td></tr>
<tr><td></td><td>View of the western portion of the site.</td></tr>
<tr><td>Photo #: Rincon Landfill 2-2</td><td>Description</td></tr>
<tr><td></td><td>View of rocks placed near the coast. Anecdotal information from nearby residents suggested that the rocks were placed there to reduce erosion of the shore.</td></tr>
</table>

Photo #: Rincon Landfill 2-3	Description
	View near the site entrance, where varying amounts of municipal waste were found.
Photo #: Rincon Landfill 2-4	Description
	View of the borehole and the bottom of the Guelph permeameter.

Photo #: Rincon Landfill 2-5	Description
	View of the western edge of the site, where debris appeared to be contacting the ocean and washing into the ocean.
Photo #: Rincon Landfill 2-6	Description
	View of stream on eastern portion of the site. Cans, bottles, and other debris were found to be placed adjacent to and in the stream.

Photo #: Rincon Landfill 2-7	Description
	View of the stream on the eastern portion of the site.
Photo #: Rincon Landfill 2-8	Description
	A fence running along a portion of the site.

Photo #: Rincon Landfill 2-9	Description
	Close-up of wall on the western portion of the site. Municipal waste (mostly consisting of metal, plastic, and glass containers) could be seen at varying depths along the wall.
Photo #: Rincon Landfill 2-10	Description
	View to the north on the western portion of the site. The wall on the right side of the photo was approximately 3 to 4 ft deep. Small pieces of municipal waste and other debris can be seen along the wall.

<table>
<tr><td>Photo #: Rincon Landfill 2-11</td><td>Description</td></tr>
<tr><td></td><td>A view farther south of photo 2-11. Debris can be seen in the cross-section of the wall.</td></tr>
</table>

Photo #: Cabo Rojo Landfill 1	Description
	View to the west, upslope. Photo taken near the facility's gated entrance.
Photo #: Cabo Rojo Landfill 2	Description
	View of the eastern slope of the landfill.

<table>
<tr><td>Photo #: Cabo Rojo Landfill 3</td><td>Description</td></tr>
<tr><td></td><td>Vegetation towards the edge of the top deck of the landfill.</td></tr>
<tr><td>Photo #: Cabo Rojo Landfill 4</td><td>Description</td></tr>
<tr><td></td><td>View of a low-lying wetland area that appeared to be outside of the landfill footprint to the northwest.</td></tr>
</table>

Photo #: Cabo Rojo Landfill 5	Description
	View from the top of the landfill looking to the northwest.
Photo #: Cabo Rojo Landfill 6	Description
	

Photo #: Cabo Rojo Landfill 7	Description
	Filling the water jug used for hydraulic conductivity testing.
Photo #: Cabo Rojo Landfill 8	Description
	View to the south from the top deck of the landfill.

Photo #: Cabo Rojo Landfill 9	Description
	View of an apparent property boundary marker towards the south side of the landfill.
Photo #: Cabo Rojo Landfill 10	Description
	View of borehole prior to hydraulic conductivity testing.

Photo #: Cabo Rojo Landfill 11	Description
	Close-up view of clayey cover excavated as part of borehole advancement for hydraulic conductivity testing.

Photo #: Vieques Landfill 1	Description
	Photo of facility sign indicating that the site is closed.

Photo #: Vieques Landfill 2	Description
	View of the landfill top deck.

Photo #: Vieques Landfill 3	Description
	View of the landfill top deck. Accumulation of debris in the midground.
Photo #: Vieques Landfill 4	Description
	Top deck of the landfill.

<table>
<tr><td>Photo #: Vieques Landfill 5</td><td>Description</td></tr>
<tr><td></td><td>View of slight surface depression. It appeared that some animals had gathered in the area based on the presence of hoof prints.</td></tr>
<tr><td>Photo #: Vieques Landfill 6</td><td>Description</td></tr>
<tr><td></td><td>Presence of visible debris on the landfill surface.</td></tr>
</table>

Photo #: Vieques Landfill 7	Description
	View of the landfill to the north. Heavy vegetation was present along the northern and western borders of the site.
Photo #: Vieques Landfill 8	Description
	View towards the north of the landfill. The beach was not accessed during the field visit to assess whether the northern edge of waste could be seen.

Photo #: Vieques Landfill 9	Description
	View of the facility entrance. The south portion of the site abutted a paved road. The facility's entrance did not have a gate or a lock. An earth berm approximately two ft high was in place to limit access.
Photo #: Vieques Landfill 10	Description
	View of the southern edge of the site from the paved access road.

Photo #: Vieques Landfill 11	Description
	
Photo #: Vieques Landfill 12	Description
	Close-up view of the cover soil at the site.

<table>
<tr><td>Photo #: Vieques Landfill 13</td><td>Description</td></tr>
<tr><td></td><td>View of a path that was worn towards the edge of the site. Several similar paths were seen throughout the site and appeared to be from the roaming of the horses.</td></tr>
<tr><td>Photo #: Vieques Landfill 14</td><td>Description</td></tr>
<tr><td></td><td>Evidence of a small, controlled burn on the landfill surface.</td></tr>
</table>

Appendix C – Rincon Landfill Hydraulic Conductivity

INNOVATIVE WASTE CONSULTING SERVICES, LLC		
6628 NW 9th Blvd., Suite 3, Gainesville, FL 32605, USA		
APPENDIX C -Field Saturated Hydraulic Conductivity of Cover Soil at Rincón 2	**ENGINEER: Brett Tooley**	**DATE: 4/5/2011**
PROJECT NAME: Puerto Rico Landfill Closure Evaluation	**CHECKED BY: Jon Powell**	**DATE: 4/8/2011**

SUBJECT: This calculation package provides the calculation of the field saturated hydraulic conductivity of the cover soil at Rincón 2 in Rincón, Puerto Rico, using field data collected with a Guelph Permeameter .

DESIGN CRITERIA AND APPROACH:

The methodology provided with the Model 2800K1 Guelph Permeameter (SoilMoisture Equipment Corp 2005) was used to calculate a steady-state rate of change value in the field, then using a series of constants and assumptions with the field data to calculate the hydraulic conductivity.

First, the top 2 to 3 inches of soil were removed using a hand auger. Following initial removal of the topsoil layer, the soil beneath was visually classified. The cover soil at the landfill was classified in accordance with the guidelines provided with the field equipment. A α* value was assigned to the soil under evaluation, where α* is the macroscopic capillary length parameter which represents the ratio of gravity to capillary forces during infiltration or drainage.

For the closed Rincón Landfill,

$$\alpha^* = 0.04 \text{ cm}^{-1}$$

Based on the value of α*, the appropriate C Factor (a numerically-derived shape factor) equation was selected. The C Factor curve, C_2, is used for conditions where α* = 0.04 cm^{-1} and is calculated as follows:

$$C_2 = \left(\frac{H/a}{1.992 + 0.091(H/a)}\right)^{0.683}$$

where,

C_2 = numerically-derived shape factor (dimensionless)
H = height of water in the well (cm)
a = well radius (cm) (always equals 3.0 cm for standardized procedure)

In the field, the steady-state rate of fall (R_{1ss}) was measured using the graduated cylinder in the Guelph Permeameter. Readings (R_1) were taken until the measurements stabilized (minimum 3 consecutive readings of equal value). R_{1ss} is calculated from measurements taken on the graduated cyclinder of the Guelph Permeameter as follows:

$$R_{1ss} = \frac{R_1}{T}$$

where,

R_1= the stabilized water level change (cm)
T = time interval between readings (sec)

INNOVATIVE WASTE CONSULTING SERVICES, LLC

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APPENDIX C -Field Saturated Hydraulic Conductivity of Cover Soil at Rincón 2	**ENGINEER: Brett Tooley**	**DATE: 4/5/2011**
PROJECT NAME: Puerto Rico Landfill Closure Evaluation	**CHECKED BY: Jon Powell**	**DATE: 4/8/2011**

The flow rate is calculated from R_{1ss} as follows:

$$Q_1 = XR_{1ss} \;\; or \;\; Q_1 = YR_{1ss}$$

The value, X, represents the cross-sectional area of the inner and outer reservoir of the instrument (this value is typically used at sites where the hydraulic conductivity is expected to be relatively high). The value Y is the cross-sectional area of the inner reservoir only (used at sites where the hydraulic conductivity is expected to be relatively low). Based on visual classification of the soil at Rincón, the combined reservoir procedure (thus the X value) was used.

The field saturated hydraulic conductivity (K_{fs}) of the cover soil at the site is calculated as follows:

$$K_{fs} = \frac{C_2 Q_1}{2\pi H_1^2 + \pi a^2 C_2 + 2\pi\left(\frac{H}{\alpha^*}\right)}$$

CALCULATIONS:

Calculating the C Factor, C_2 :

H = 5 cm

a = 3 cm

C_2 = 0.842

Calculating the Flow Rate, Q_1 :

$$C_2 = \left(\frac{H/a}{1.992 + 0.091(H/a)}\right)^{0.683}$$

Table 1. Field Data

Reading	*Elapsed Time (sec)*	*Time Interval (sec)*	*Water Level (cm)*	*Water Level Change, R_1 (cm)*	Rate of Water Level Change (cm/s)
0	0	0	0.0	0.0	0.00E+00
1	120	120	2.0	2.0	1.67E-02
2	240	120	3.1	1.1	9.17E-03
3	360	120	3.8	0.7	5.83E-03
4	480	120	4.5	0.7	5.83E-03
5	720	240	5.7	1.2	5.00E-03
6	840	120	6.2	0.5	4.17E-03
7	960	120	6.7	0.5	4.17E-03
8	1080	120	7.2	0.5	4.17E-03

Note that the elapsed time between the 4th and 5th reading was 4 minutes whereas all other readings were taken at 2 minute intervals.

R_1 = 0.50 cm

T = 120 sec

$$R_{1ss} = \frac{R_1}{T}$$

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APPENDIX C -Field Saturated Hydraulic Conductivity of Cover Soil at Rincón 2	**ENGINEER: Brett Tooley**	**DATE: 4/5/2011**
PROJECT NAME: Puerto Rico Landfill Closure Evaluation	**CHECKED BY: Jon Powell**	**DATE: 4/8/2011**

R_{1ss} = 4.17E-03 cm/sec

X = 35.22 cm^2

Q_1 = 0.147 cm^3/sec

$$Q_1 = XR_{1ss}$$

Calculating the hydraulic conductivity, K_{fs}:

K_{fs} = 1.3E-04 cm/sec

$$K_{fs} = \frac{C_2 Q_1}{2\pi H_1^2 + \pi a^2 C_2 + 2\pi\left(\frac{H}{\alpha^*}\right)}$$

CONCLUSION:

The calculated field saturated hydraulic conductivity of the cover soil at Rincón 2 was 1.3 x 10^{-4} cm/sec.

REFERENCES:

SoilMoisture Equipment Corp (2005). Model 2800K1 Guelph Permeameter Operating Instructions. Santa Barbara, CA.

Appendix D – Cabo Rojo Landfill Hydraulic Conductivity

INNOVATIVE WASTE CONSULTING SERVICES, LLC		
6628 NW 9th Blvd., Suite 3, Gainesville, FL 32605, USA		
APPENDIX D -Field Saturated Hydraulic Conductivity of Cover Soil for Cabo Rojo Landfill	ENGINEER: Brett Tooley	DATE: 4/5/2011
PROJECT NAME: Puerto Rico Landfill Closure Evaluation	CHECKED BY: Jon Powell	DATE: 4/8/2011

SUBJECT: This calculation package provides the calculation of the field saturated hydraulic conductivity of the cover soil at the closed Cabo Rojo Landfill in Cabo Rojo, Puerto Rico, using field data collected using a Guelph Permeameter .

DESIGN CRITERIA AND APPROACH:

The methodology provided with the Model 2800K1 Guelph Permeameter (SoilMoisture Equipment Corp 2005) was used to calculate a steady-state rate of change value in the field, then using a series of constants and assumptions with the field data to calculate the hydraulic conductivity.

First, the top 3 or 4 inches of soil were removed using a hand auger. Following initial removal of the topsoil layer, the soil beneath was visually classified. The cover soil at the landfill was classified in accordance with the guidelines provided with the field equipment. A α* value was assigned to the soil under evaluation, where α* is the macroscopic capillary length parameter which represents the ratio of gravity to capillary forces during infiltration or drainage.

For the closed Cabo Rojo Landfill,

$$\alpha^* = 0.01\ \text{cm}^{-1}$$

Based on the value of α*, the appropriate C Factor (a numerically-derived shape factor) equation was selected. The C Factor curve, C_3 is used for conditions where $\alpha^* = 0.01\ \text{cm}^{-1}$ and is calculated as follows:

$$C_3 = \left(\frac{H/a}{2.081 + 0.121(H/a)}\right)^{0.672}$$

where,

C_3 = numerically-derived shape factor (dimensionless)
H = height of water in the well (cm)
a = well radius (cm) (always equals 3.0 cm for standardized procedure)

In the field, the steady-state rate of fall (R_{1ss}) was measured using the graduated cylinder in the Guelph Permeameter. Readings (R_1) were taken until the measurements stabilized (minimum 3 consecutive readings of equal value). R_{1ss} is calculated from measurements taken on the graduated cylinder of the Guelph Permeameter as follows:

$$R_{1ss} = \frac{R_1}{T}$$

where,

R_1= the stabilized water level change (cm)
T = time interval between readings (sec)

Innovative Waste Consulting Services, LLC

for Cabo Rojo Landfill	ENGINEER: Brett Tooley	DATE: 4/5/2011
PROJECT NAME: Puerto Rico Landfill Closure Evaluation	CHECKED BY: Jon Powell	DATE: 4/8/2011

The flow rate is calculated from $R_{1s,s}$ as follows:

$$Q_1 = XR_{1ss} \;\; or \;\; Q_1 = YR_{1ss}$$

The value, X, represents the cross-sectional area of the inner and outer reservoir of the instrument (this value is typically used at sites where the hydraulic conductivity is expected to be relatively high). The value Y is the cross-sectional area of the inner reservoir only (used at sites where the hydraulic conductivity is expected to be relatively low). At Cabo Rojo, the inner reservoir was used while taking measurements, thus the Y value was used to calculate Q.

The field saturated hydraulic conductivity (K_{fs}) of the cover soil at the site is calculated as follows:

$$K_{fs} = \frac{C_3 Q_1}{2\pi H_1^2 + \pi a^2 C_3 + 2\pi\left(\frac{H}{\alpha^*}\right)}$$

CALCULATIONS:

Calculating the C Factor, C_3:

H = 5 cm

a = 3 cm

C_3 = 0.809

$$C_3 = \left(\frac{H/a}{2.081 + 0.121(H/a)}\right)^{0.672}$$

Calculating the Flow Rate, Q_1:

Table 1. Field Data

Reading	*Elapsed Time (sec)*	*Time Interval (sec)*	*Water Level (cm)*	*Water Level Change, R_1 (cm)*	Rate of Water Level Change (cm/s)
1	22	0	32.9	0.0	0.00E+00
2	82	60	38.5	5.6	9.33E-02
3	142	60	42.9	4.4	7.33E-02
4	202	60	44.9	2.0	3.33E-02
5	262	60	47.0	2.1	3.50E-02
6	322	60	48.2	1.2	2.00E-02
7	382	60	49.2	1.0	1.67E-02
8	442	60	50.7	1.5	2.50E-02
9	502	60	51.4	0.7	1.17E-02
10	562	60	52.3	0.9	1.50E-02
11	682	120	54.3	2.0	1.67E-02
12	862	180	56.3	2.0	1.11E-02
13	982	120	58.5	2.2	1.83E-02
14	1162	180	59.9	1.4	7.78E-03

Continued on Next Page

Innovative Waste Consulting Services, LLC

	ENGINEER: Brett Tooley	DATE: 4/5/2011
PROJECT NAME: Puerto Rico Landfill Closure Evaluation	CHECKED BY: Jon Powell	DATE: 4/8/2011

Continued from Previous Page

15	1342	180	62.1	2.2	1.22E-02
16	1522	180	63.5	1.4	7.78E-03
17	1702	180	65.4	1.9	1.06E-02
18	1882	180	67.1	1.7	9.44E-03
19	2062	180	68.6	1.5	8.33E-03
20	2242	180	70.1	1.5	8.33E-03
21	2422	180	71.6	1.5	8.33E-03

$$R_{1ss} = \frac{R_1}{T}$$

R_1 = 1.50 cm

T = 180 sec

$$Q_1 = XR_{1ss}$$

R_{1ss} = 8.33E-03 cm/sec

Y = 2.15 cm^2

Q_1 = 0.018 cm^3/sec

Calculating the hydraulic conductivity, K_{fs}:

$$K_{fs} = \frac{C_3 Q_1}{2\pi H_1^2 + \pi a^2 C_3 + 2\pi \left(\frac{H}{\alpha^*}\right)}$$

K_{fs} = 4.4E-06 cm/sec

CONCLUSION:

The calculated field saturated hydraulic conductivity of the cover soil at the closed Cabo Rojo Landfill was 4.4×10^{-6} cm/sec.

REFERENCES:

SoilMoisture Equipment Corp (2005). Model 2800K1 Guelph Permeameter Operating Instructions. Santa Barbara, CA.

Appendix E – Viegues Landfill Hydraulic Conductivity

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APPENDIX E -Field Saturated Hydraulic Conductivity of Cover Soil at the Vieques Landfill	**ENGINEER: Brett Tooley**	**DATE: 4/5/2011**
PROJECT NAME: Puerto Rico Landfill Closure Evaluation	**CHECKED BY: Jon Powell**	**DATE: 4/8/2011**

SUBJECT: This calculation package provides the calculation of the field saturated hydraulic conductivity of the cover soil at the closed Vieques Landfill in Vieques, Puerto Rico, using field data collected with a Guelph Permeameter .

DESIGN CRITERIA AND APPROACH:

The methodology provided with the Model 2800K1 Guelph Permeameter (SoilMoisture Equipment Corp 2005) was used to calculate a steady-state rate of change value in the field, then using a series of constants and assumptions with the field data to calculate the hydraulic conductivity.

First, the top 2 to 3 inches of soil were removed using a hand auger. Following initial removal of the topsoil layer, the soil beneath was visually classified. The cover soil at the landfill was classified in accordance with the guidelines provided with the field equipment. A α* value was assigned to the soil under evaluation, where α* is the macroscopic capillary length parameter which represents the ratio of gravity to capillary forces during infiltration or drainage.

For the closed Vieques Landfill,

$\alpha^* =$ 0.04 cm^{-1}

Based on the value of α*, the appropriate C Factor (a numerically-derived shape factor) equation is selected. The C Factor curve, C_2, is used for conditions where $\alpha^* = 0.04\ cm^{-1}$ and is calculated as follows:

$$C_2 = \left(\frac{H/a}{1.992 + 0.091(H/a)}\right)^{0.683}$$

where, C_2 = numerically-derived shape factor (dimensionless)
H = height of water in the well (cm)
a = well radius (cm) (always equals 3.0 cm for standardized procedure)

In the field, the steady-state rate of fall (R_{1ss}) was measured using the graduated cylinder in the Guelph Permeameter. Readings (R_1) were taken until the measurements stabilized (minimum 3 consecutive readings of equal value). R_{1ss} is calculated from measurements taken on the graduated cylinder of the Guelph Permeameter as follows:

$$R_{1ss} = \frac{R_1}{T}$$

where,
R_1= the stabilized water level change
(cm) T = time interval between readings (sec)

The flow rate is calculated from R_{1ss} as follows:

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PROJECT NAME: Puerto Rico Landfill Closure Evaluation	**CHECKED BY: Jon Powell**	**DATE: 4/8/2011**

$$Q_1 = XR_{1ss} \ \ or \ \ Q_1 = YR_{1ss}$$

The value, X, represents the cross-sectional area of the inner and outer reservoir of the instrument (this value is typically used at sites where the hydraulic conductivity is expected to be relatively high). The value Y is the cross-sectional area of the inner reservoir only (used at sites where the hydraulic conductivity is expected to be relatively low). Based on visual classification of the soil at Vieques, the combined reservoir procedure (thus the X value) was used.

The field saturated hydraulic conducivity (Kfs) of the cover soil at the site is calculated as follows:

$$K_{fs} = \frac{C_2 Q_1}{2\pi H_1^2 + \pi a^2 C_2 + 2\pi\left(\frac{H}{\alpha^*}\right)}$$

CALCULATIONS:

Calculating the C Factor, C_2:

$$C_2 = \left(\frac{H/a}{1.992 + 0.091(H/a)}\right)^{0.683}$$

H = 5 cm

a = 3 cm

C_2 = 0.842

Table 1. Field Data

Reading	*Elapsed Time (sec)*	*Time Interval (sec)*	*Water Level (cm)*	*Water Level Change, R_1 (cm)*	Rate of Water Level Change (cm/s)
0	0	0	0.0	0.0	0.00E+00
1	120	120	4.6	4.6	3.83E-02
2	240	120	5.8	1.2	1.00E-02
3	360	120	6.5	0.7	5.83E-03
4	480	120	7.2	0.7	5.83E-03
5	600	120	7.8	0.6	5.00E-03
6	720	120	8.3	0.5	4.17E-03
7	840	120	8.8	0.5	4.17E-03
8	960	120	9.2	0.4	3.33E-03
9	1080	120	9.6	0.4	3.33E-03
10	1200	120	9.9	0.3	2.50E-03
11	1320	120	10.2	0.3	2.50E-03
12	1440	120	10.6	0.4	3.33E-03
13	1560	120	10.9	0.3	2.50E-03
14	1680	120	11.3	0.4	3.33E-03
15	1800	120	11.6	0.3	2.50E-03
16	1920	120	11.8	0.2	1.67E-03
17	2040	120	12.2	0.4	3.33E-03

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The rate of change between the 16th and 34th minute of testing continued oscillating around a central value, which was selected to be a rate of change of 0.35 cm per interval.

R_1 = 0.35cm

T = 120 sec

$$R_{1ss} = \frac{R_1}{T}$$

R_{1ss} = 2.92E-03 cm/sec X = 35.22 cm^2

Q_1 = 0.103 cm^3/sec

$$Q_1 = XR_{1s}$$

Calculating the hydraulic conductivity, K_{fs}:

K_{fs} = 9.0E-05 cm/sec

$$K_{fs} = \frac{C_2 Q_1}{2\pi H_1^2 + \pi a^2 C_2 + 2\pi\left(\frac{H}{\alpha^*}\right)}$$

CONCLUSION:

The calculated field saturated hydraulic conductivity of the cover soil at the closed Vieques Landfill was 9.0 x 10^{-5} cm/sec.

REFERENCES:

SoilMoisture Equipment Corp (2005). Model 2800K1 Guelph Permeameter Operating Instructions. Santa Barbara, CA.

Appendix F – Supplemental Site Figures: An Evaluation and Analysis of Past Landfill Closures in Puerto Rico as Guidance for Current and Future Closures

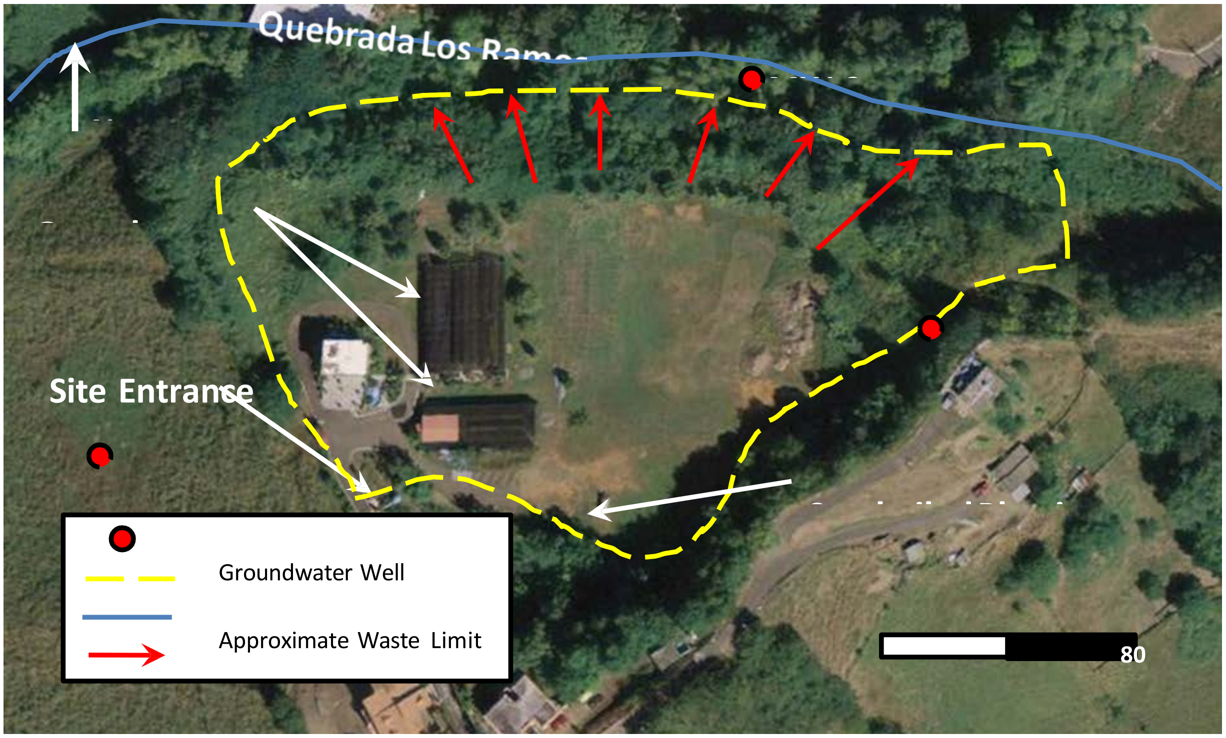

Figure F-1. Aerial Photograph of the Rincón Municipal Landfill with Supplemental Site Information.

1. Groundwater well locations are approximate based on information gathered from a site inspection conducted by EQB in February 2002.
2. The downward surface grade arrows shown in the figure are conceptual and represent only relatively steep slopes as identified in the field by the project team.
3. The waste limit shown is approximate based on information provided in the closure plan prepared for the site by Garcia, Cabot y Asociados in 1994.
4. The location of the stream, "Quebrada Los Ramos," is approximate and was adapted from a similar depiction within Google Maps.
5. The location of the stockpiled plastics is approximate and is based on the visual observations of the project team during the site visit.
6. The closed landfill has been used as a plant nursery for an unknown period of time. Historical documents indicate that the municipality sought permission for an alternative use of the landfill sometime before March 2002. Greenhouses and numerous potted plants were found at the site during the site visit.

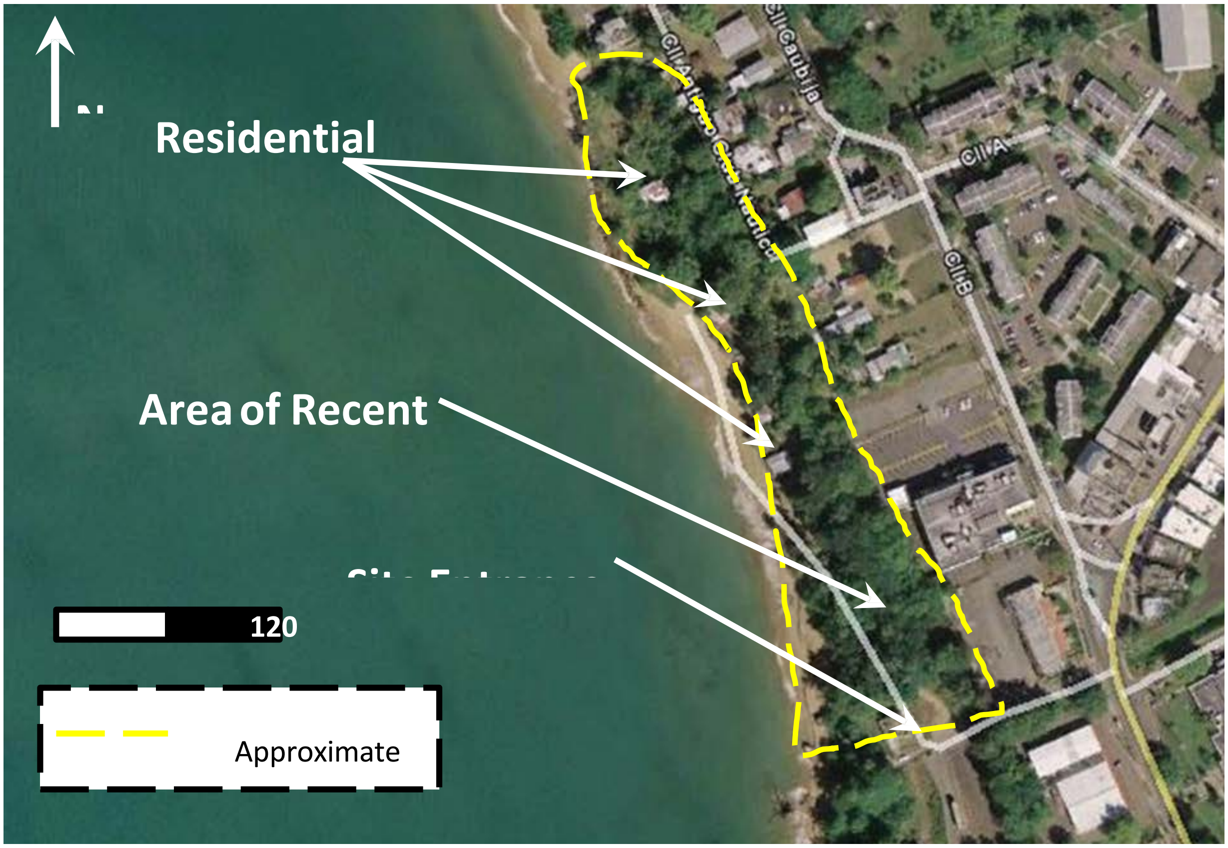

Figure F-2. Aerial Photograph of the Closed Rincón Landfill with Supplemental Site Information.

1. The waste limit shown is approximate based on information gathered in the field.
2. The “Area of Recent Waste Deposits” shown in the figure points to the general location where apparently fresh garbage had been deposited. Numerous discrete piles were observed throughout the site; however, the piles were predominantly concentrated at the south end of the site near the entrance.
3. Inhabitants of the buildings identified in the figure confirmed that the structures constructed on the landfill surface were, in fact, residential buildings.

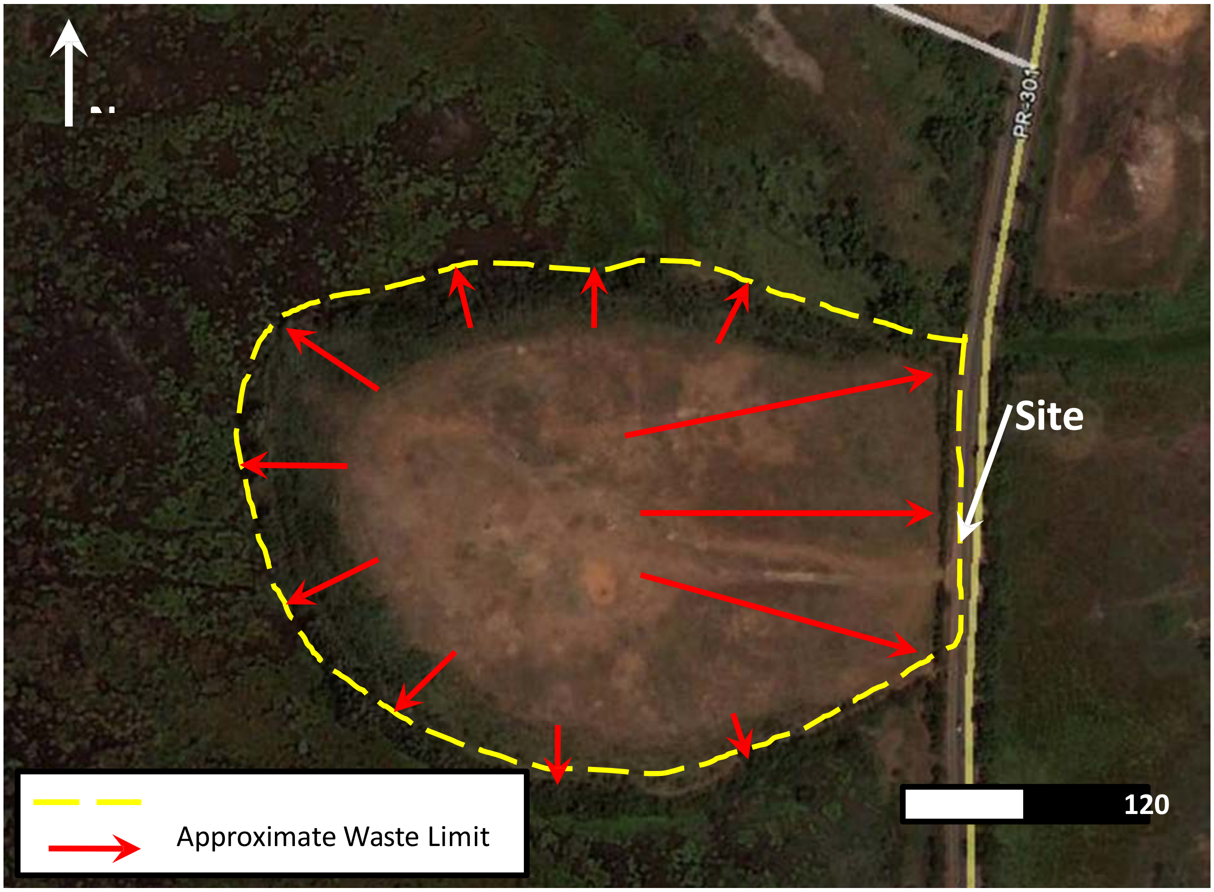

Figure F-3. Aerial Photograph of the Cabo Rojo Municipal Landfill with Supplemental Site Information.

1. The downward surface grade arrows shown in the figure are conceptual and represent only relatively steep slopes as identified in the field by the project team.
2. The waste limit shown is approximate based on information provided in the closure plan prepared for the site by Jordan, Jones, and Goulding in 1994, and information gathered in the field.

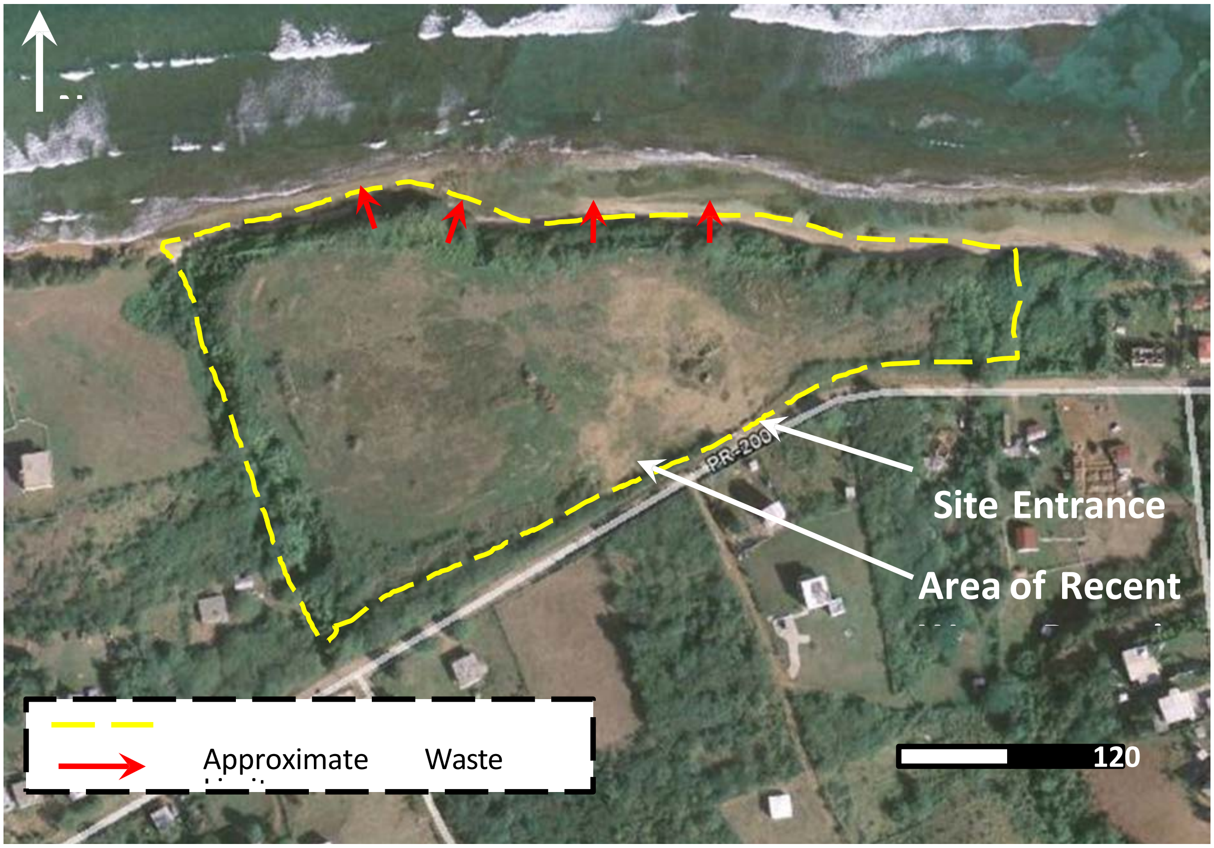

Figure F-4. Aerial Photograph of the Closed Vieques Landfill with Supplemental Site Information.

1. The downward surface grade arrows shown in the figure are conceptual and represent only relatively steep slopes as identified in the field by the project team. The site was predominantly flat with the only significant elevation change observed at the north end adjacent to the beach.
2. The waste limit shown is approximate based on information gathered in the field.
3. The "Area of Recent Waste Deposits" shown in the figure points to the general location where apparently fresh garbage had been deposited. Discrete piles were observed throughout the site.